THE IMPACTS OF NEIGHBOURHOOD TRAFFIC MANAGEMENT

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Basil David Daniel

Department of Civil and Natural Resources Engineering

University Of Canterbury

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For my mother Stella and my late father David.

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ABSTRACT

A major traffic-related problem faced by residents is speeding, which not only causes safety concerns, but also noise issues. Traffic calming is a much favoured traffic management tool employed by road controlling authorities to primarily reduce vehicle speed, hence improve community liveability.

This research aimed to investigate the impacts of traffic calming on speed, safety and traffic noise. The objectives included developing models for the prediction of speed and noise on traffic-calmed streets, and providing guidance for good design practices.

Speeds of individual vehicles as they approached and crossed traffic calming devices were observed in order to identify the behaviour of individual drivers. Results indicated that the speed hump and the raised angled slow point produced the largest speed reductions and least variation in speeds, while mid-block narrowings had no significant speed changes. Inter-device speed was found to be mainly controlled by the separation between devices.

85th percentile speeds at distances from calming devices were 40 – 45 km/h for vertical deflections and 45 – 55 km/h for horizontal deflections. Speeds on approach to speed humps were found to be influenced by the distance available on the approaches, while operating speed at the speed humps were partly influenced by the hump width relative to the road width.

There was evidence of safety benefits of traffic calming overall, despite mid-block crashes increasing post-calming. However, there was no association between the traffic calming and the crashes, which appeared to probably be due to other factors, human factors in particular.

Noise levels produced by light vehicles across speed humps were in fact lower than on a flat section of road, given their respective mean speeds. At a reference speed of 25 km/h, noise levels produced over the 100 mm hump were 3.6 dBA higher than those produced by the 75 mm hump.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY OF TERMS

The following explains some of the technical terms that are mentioned in this document. These terms are common terminology used in transportation engineering, acoustics and statistics, though some may be specifically used for this research only.

Term	*Description*
85th percentile speed	The speed which 85% of the vehicles travel at or below.
AADT	Annual Average Daily Traffic, which is the total yearly volume of traffic on both directions divided by the number of days in a year.
AC	Asphaltic Concrete, which is a composite material made up of aggregates and asphalt that is used for construction of road surfaces, airport runways and parking lots.
ANOVA	Acronym for “analysis of variance”.
Advisory speed	The recommended maximum speed at which a section of roadway should be negotiated for comfort and safety.
Angled slow point	A road narrowing with its travel path deflected at an angle.
Approach length	The distance between a traffic calming device from a street entry or bend.
Approach speed	The highest observed 85th percentile speed on the approach to an isolated traffic calming device or the first device used in a series.
Arterial road	A high-capacity road that delivers traffic between urban centres. May simply be referred to as **arterial**.

Term	*Description*
Austroads	The association of Australian and New Zealand road transport and traffic authorities.
Background noise	Noise other than those produced by traffic. Sometimes called **residual noise**.
CAS	Crash Analysis System, which is an integrated computer system that provides tools to collect, map, query, and report on road crash and related data. It contains data from all traffic crashes reported by police.
Carriageway	The portion of road that is dedicated to the use of vehicles.
Channel	The drain that directly receives surface runoff from the pavement.
Chip seal	A thin layer of binder sprayed onto a pavement surface with a layer of aggregate incorporated and which is impervious to water. Also called **spray seal.**
Collector road	A road that delivers traffic from local streets to arterials. May simply be referred to as **collector**.
Crash	An event involving one or more road vehicles that results in personal physical injury and/or damage to property. Also called **accident** or **collision**.
Crash rate	The ratio of number of crashes to a common denominator, such as period of time, or vehicle-kilometres travelled.
Cut-through	The act of driving through a street for the intention of using it as a short-cut or avoiding congested streets. Also called **short-cutting** and **rat running**.

Term	*Description*
DUSL	Abbreviation for “default urban speed limit”.
Device	An individual engineering treatment introduced in a street carriageway.
Device operating speed	The observed 85th percentile speed of vehicles negotiating a traffic calming device. May also be simply referred to as **operating speed**.
Entrance treatment	Visual and physical alterations at the entry to a street to mark a change in speed environment. Employs textured surface and carriageway narrowing, among others. Also called **threshold treatment** and **gateway treatment**.
Farside lane	The travel lane that is furthest from the observation point.
Fatal crashes	Crashes where at least one person is killed.
Flush	Binder at same level as top of sealing chips.
Heavy vehicle	A two-axle vehicle with the minimum axle spacing greater than 3.2 m, or a three- or more-axle vehicle with at least two axle groups. Weighs more than 3.5 tonnes.
Horizontal deflections	Traffic calming devices that create lateral shifts and constrictions in the roadway to slow down vehicles.
Idling engine noise	Noise produced by stationary vehicles with engines left running.
Impeded segment	The section of road that is restrained by a traffic calming device.
Injury crashes	Crashes where at least one person is injured or killed. Also referred to as **casualty crashes**.

Term	*Description*
Inter-device speed	The highest observed 85th percentile speed between consecutive traffic calming devices.
Intersection crashes	Crashes occurring where two or more streets intersect. Includes crashes that occur within 30 m from the intersection.
LATM	Local Area Traffic Management, which is an area-wide traffic calming scheme involving a cluster of streets.
LIDAR	Acronym for “light detection and ranging”.
Light vehicles	All vehicles other than those defined as heavy vehicles. Includes cars, vans, sports utility vehicles (SUV), and multi-purpose vehicles (MPV), with or without a trailer on tow.
Local roads	All roads other than State Highways.
Local streets	Roads that provide access to homes to those who enter and leave, and to those who deliver and collect. Also referred to as **residential streets** and **local access roads**. Not to be confused with “local roads”.
Mean speed	The time mean speed, which is the summation of vehicle speeds at a specific location divided by the number of vehicles observed.
Mid-block	The section of road (or “link”) between two intersections (or “nodes”).
Mid-block crashes	Crashes occurring at mid-block or all other crashes apart from intersection crashes.

Term	*Description*
Minor injuries	Non-serious injuries that may cause some discomfort or pain, and which may require first aid. Also referred to as **slight injuries**.
Multiple devices	Two or more traffic calming devices used in a series. Also called **sequential devices**.
NZTA	New Zealand Transport Agency, the government agency for funding land transport.
Narrowing	A constricted roadway segment formed by kerb extensions or traffic islands at mid-block. Also known as **choker** or **bulbous kerb**.
Nearside lane	The travel lane that is closest to the kervside observation point.
Neckdown	A narrowing at the entry to a street, formed by kerb extensions or traffic islands.
Neighbourhood	Portion of a suburb or other urban area, defined by geographical boundaries (natural and man-made) and having common community services.
Noise differential	The difference between the noise level observed when a vehicle is in motion and the idling engine noise.
Non-injury crashes	Crashes where no one is injured or killed, and may involve damage to property only.
OGPA	Abbreviation for “open graded porous asphalt”, which is an asphalt mix designed with large voids that allow rapid draining of surface water.

Term	*Description*
Off-peak period	The periods that have low demand volumes during the day.
Pavement	That portion of a road designed for the support of, and to form the running surface for, vehicular traffic.
Peak period	The periods that have high demand volumes during the day.
RCA	Road Controlling Authorities, which are responsible for managing roads under their jurisdiction. Typically these are either city/district councils (for local roads) or NZTA (for State Highways).
RTN	Abbreviation for "road traffic noise".
Ramp	An inclined plane incorporated in the design of vertical deflections to provide smoother transition of vehicles from the pavement to the device, and vice versa.
Regression	A statistical technique used to develop a mathematical relationship between two or more variables. Same as **statistical regression** or **regression analysis**.
Roadway	Any one part of the width of a road that is dedicated to the use of vehicles. Traditionally, this is from kerb to kerb.
S-curve	Short for **Sigmoid curve**, it is a curve having an "S" shape.
SPB	Abbreviation for "statistical pass-by", a method originally designed for measuring tyre-road noise.
Serious injuries	Injuries requiring medical attention or admission to hospital.

Term	*Description*
Single device	A single traffic calming device used with no other devices around. Also referred to as **isolated device**.
Side road crashes	Crashes occurring where a local street intersects with a side road. A side road crash is a type of intersection crash.
Sound level meter	An instrument for measuring sound levels.
Spacing	The distance between consecutive traffic calming devices.
Speed change	The drop from street speed to device operating speed.
Speed differential	The difference in the speed at a distance from a traffic calming device and the device operating speed.
Speed gun	An instrument used to measure speed and range. Also called **radar gun** or **speed meter**.
Speed hump	A raised section of pavement placed across a street to force motorists to travel at lower speeds. Has circular, parabolic or sinusoidal profiles, but may also be trapezoidal (see *speed table*). Also referred to as **road hump**, **round-top hump** or **hump**.
Speed limit	The maximum legal speed that vehicles are allowed to be driven on roads. In New Zealand, the default urban speed limit is 50 km/h, while the rural speed limit is 100 km/h or lower.
Speed profile	The observed or estimated changes in vehicle speed along a road. Usually displayed as a speed versus distance plot.

Term	*Description*
Speed table	A variant of the speed hump, having a trapezoidal profile. Also referred to as **flat-top hump**, **plateau**, **platform** or **table**.
Speed variance	A measure of how far vehicle speeds are spread out from the mean speed at a given road or section of road. Also referred to as **variation in speed**.
Standard deviation	A measure of variation from the mean value. It is the square root of variance.
Standard error	The standard deviation of the sampling distribution of a statistic.
Street speed	The 85^{th} percentile speed observed on a street.
Street-end crashes	Crashes occurring where a local street intersects with a collector or arterial. A street-end crash is a type of intersection crash.
Target speed	The speed that is expected to be achieved through the implementation of speed control measures. Also referred to as **desired speed**.
Textured surface	A pavement using interlocking paving blocks, i.e. blocks of material cut into regular shape and size. Also referred to as **textured pavement**.
Traffic calming	A form of traffic management that involves changes in street alignment, installation of barriers, and other physical measures to reduce traffic speeds and/or cut-through volumes, in the interest of street safety, liveability, and other public purposes.

Term	*Description*
Traffic management	The use of traffic engineering techniques to control the flow of vehicles.
Traffic volume	The number of vehicles passing a point during a known period of time. Sometimes referred to as **traffic flow**.
Travel lane	That portion of a carriageway assigned to moving traffic and does not include areas dedicated to kerbside parking. Also referred to as **travel path**.
Treatment	A general term which covers all types of physical actions (including devices) to manage traffic and/or adapt the street environment at the local level.
Unimpeded segment	The section of road that is not restrained by a traffic calming device.
Vertical deflections	Traffic calming devices that feature raised segments to slow down vehicles.
Watts profile hump	A speed hump with a specific circular profile designed to slow vehicles down.
Zone of influence	The area over which a traffic calming device produces a noticeable speed-reducing effect. It can be estimated from speed profiles, and is basically the distance between the point where speed starts to reduce and the point which corresponds with the device operating speed.

1 Introduction

Managing speed in neighbourhoods is a challenging task as there are many factors to be considered in the design and implementation of traffic calming measures, such as finance, practicability, and community response. A lot of work has been done in the past to evaluate the effectiveness of these measures and to ensure good practices. The results of this research add to that pool of knowledge, and in particular, it adds information regarding the behaviour of drivers in New Zealand when confronted with traffic calming devices.

1.1 Background to the research

Speeding has been identified as one of the major contributors to road deaths in New Zealand with 32% of fatal crashes being attributed to excessive speeds for the years 2008 to 2010. Speeding alone contributed to 15% of these crashes, while speeding associated with alcohol or drug intake accounted for 17%. On urban roads, speeding contributed to 31% of road fatalities (Ministry of Transport, 2011a).

The problem of speeding is widespread on urban roads. In 2011, 59% of car drivers were found to have exceeded the urban speed limit of 50 km/h. This was reflected by the high 85th percentile and mean speeds of 57 km/h and 52 km/h, which happen to be the lowest observed values for several decades in New Zealand (Ministry of Transport, 2011b).

The drop in urban speed levels over the last few decades may be attributed to road safety strategies that included the implementation of speed control measures and tougher enforcement of speed limits.

Empirical studies commonly associate speeding with crashes, especially more severe crashes, and it is frequently suggested that crash frequency and severity can be significantly lowered by simply reducing speeds. One way of achieving this is through behaviour modification. The most common approach of changing driver behaviour in residential zones is through traffic calming (Shinar, 2007).

Traffic calming has been widely used in New Zealand to enhance safety on local streets. It is a form of traffic management that involves physical alterations to the street in order to slow down vehicles and discourage cut-through traffic. It also creates safe and pleasant street environments for walking, cycling, playing and other communal activities.

While there have been efforts to monitor the performance of traffic calming in New Zealand, not many in-depth studies have been conducted and the findings published. Publications on traffic calming experience in New Zealand are relatively scarce compared to neighbouring Australia and countries with a long history of traffic calming, such as the Netherlands, Germany, Denmark, Britain and the United States.

This research, while making up for the aforesaid shortage, also served to offer a better understanding of the application and performance of traffic calming devices, and to provide guidance for good practices in the design of speed control measures.

1.2 Research objectives

The aim of this research was to investigate the impacts of traffic calming on speed, safety and traffic noise. To achieve this purpose, the following objectives were drawn up:

(a) To produce speed profiles of various traffic calming devices for the assessment of drivers' speed choice and performance of traffic calming devices.

(b) To determine the speed-reducing effect and the extent of zones of influence produced by traffic calming devices.

(c) To examine the variation of speeds at traffic calming devices.

(d) To study the influence of device width on device operating speed.

(e) To develop models for the prediction of speed on the approach to devices and between consecutive devices.

(f) To assess the impact of the implementation of traffic calming measures on crash rates.

(g) To investigate the effect of speed humps on light vehicle noise emissions.

(h) To develop models for the prediction of noise levels produced by light vehicles across speed humps.

1.3 Thesis Outline

This thesis is a documentation of work that included reviewing past literature, designing research methods, analysing raw data, improving on methods for conducting data collection and analysis, making new discoveries, and turning findings into significant contributions to the state of the art. It is presented in five main chapters:

Chapter Two extensively covers literature on various topics relevant to this research, such as driver speed choice, the influence of speed on road crashes, justification for the need to lower residential speed limits, how safer streets can be achieved through behavioural changes, the benefits and issues of traffic calming, and previous research carried out on the estimation of speed and noise.

Chapter Three details the procedures applied in conducting this research. It identifies study locations, describes the methods and instruments used for obtaining speed, crash and noise data, depicts the experimental set ups for data collection, and explains comparative and statistical analyses performed in this research.

Chapter Four comprehensively reports the outcomes of studies carried out to determine the effects of traffic calming devices on drivers' choice of speed on impeded and unimpeded segments of traffic-calmed streets, evaluating the performance of these devices in terms of speed reduction, investigating the effects on safety and the environment, developing methods for the estimation of speeds and noise levels on traffic calmed streets, and providing guidance for good practice.

Chapter Five discusses the findings, makes comparisons with previous work, and discusses some of the constraints encountered during the course of this research.

Chapter Six summarises the key findings of this research, highlights the contributions of this research in the field of neighbourhood traffic management, and offers suggestions for future research.

2 Literature Review

2.1 Introduction

A study by Appleyard et al. (1976) found that San Francisco residents were more bothered by traffic than by crime, where 42 percent felt their street was quite or very dangerous because of traffic, whereas only 16 percent felt it was dangerous because of crime.

Residents' fear of traffic and their call for safer streets are further justified with reports from Australia stating that 42 percent of all casualty crashes occurred on residential streets and their intersections with the arterial system, and that the casualty crash rate on residential streets was more than 50 percent higher than on arterials (Harper, 1970; cited in Brindle, 1995).

Speeding is defined as speed that is too fast for conditions or in excess of the posted speed limit. Despite lower traffic volumes, local streets and collectors in America have speeding fatality rates almost triple that of interstate highways and these numbers make up 47% of the total speeding-related crashes (FHWA, 2000).

Traffic will still remain a threat to residents unless speeding is curbed. A study disclosed that approximately two-thirds of all crashes in which people are killed or injured happen on roads with a speed limit of 30 mph (48 km/h) or less (RoSPA, 1996).

Engwicht (1992) defines a relationship between the speed of traffic and the attitude of motorists towards pedestrians, which is, fast flowing traffic reinforces the drivers' perception that the street is their territory. Tranter and Doyle (1996) argue that traffic is denying children the freedom to play on residential streets because parents are not allowing them to, for fear of traffic danger associated with the dominance of motorised traffic. Fortunately, new design philosophies (such as traffic calming) have led to a revolution in the way residential streets are perceived, one such perception being that streets are not for the sole use of cars.

2.2 Speed, safety and the driver

Speeding in residential areas can be partly attributed to a driver's perception of safe speed. For roads with lower speed limits, drivers' perceptions of safe speed are commonly higher than the legal speed, despite drivers being aware of the speed limit (Shinar, 2007).

In New Zealand and many parts of the world, the general speed limit for urban traffic areas including residential precincts is set at 50 km/h. This seems high for local streets, considering that these streets do not serve high traffic volumes or speeds, and are accorded the lowest design standard. The primary function of local streets is to provide access to homes to those who enter or leave, and those who deliver and collect. Through traffic is not encouraged but that alone is not enough to deter some motorists from using these streets as shortcuts.

2.2.1 The association between speed and road safety

Speed is fundamentally associated with road safety. Speed has been found to be a major causative factor in about 10% of all crashes and 30% of fatal crashes (TRB, 1998). In New Zealand, speeding was a factor in 32% of fatal crashes, 16% of serious injury crashes and 12% of minor injury crashes for the years 2008 to 2010 (Ministry of Transport, 2011a).

The effects of speed on road safety can be simply explained through the laws of physics related to speed in the "driver-vehicle" relationship. Moving vehicles accumulate kinetic energy, which increases with the square of speed. During a collision, the impact speed determines the amount of energy to be dissipated and, subsequently, the likelihood of injury. The force imparted on an occupant during a collision with an impact speed of 30 km/h is about 20 times the driver's weight (1,500 kg). At 50 km/h, the force is equivalent to a three-storey fall, while at 100 km/h, it is akin to a 13-storey fall (Sergerie, 2008).

Stopping sight distance, which is the sum of reaction and braking distances, also increases with speed. This means that a vehicle moving at a higher speed is more likely to collide with an obstacle in its path.

Figure 2.1 shows that a longer distance is required for a vehicle (modern, with good brakes and tyres) to stop if it is moving at a higher speed and on a wet road. The figure also demonstrates that the likelihood of a vehicle colliding with a person 45 m ahead in its path and the resultant impact speed increase at a higher speed and in wet conditions.

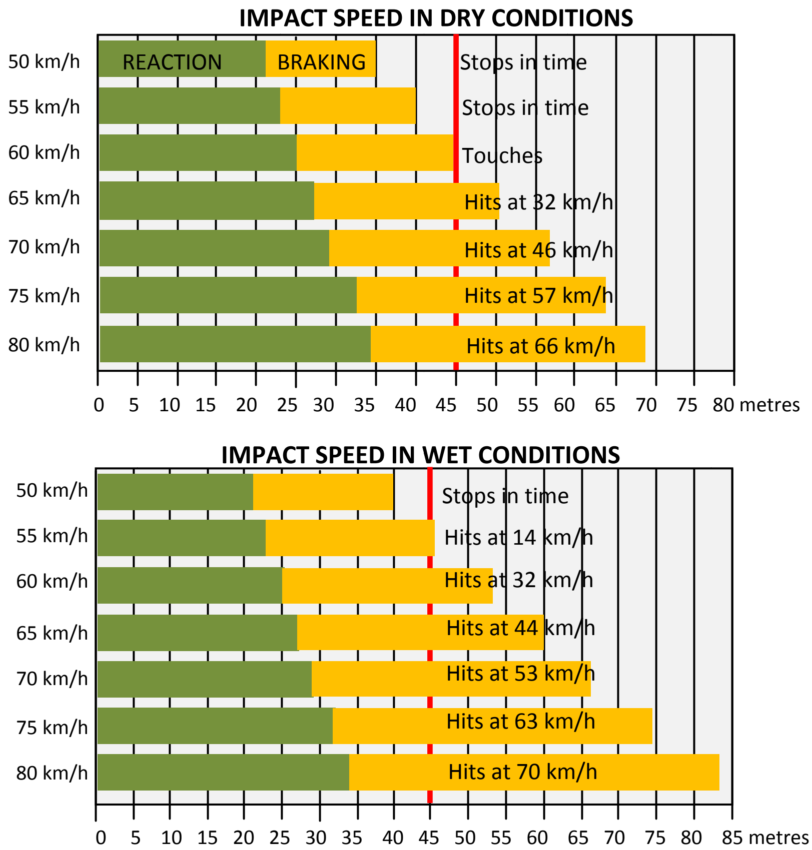


Figure 2.1 – Stopping distance at various speeds in dry and wet conditions adapted from Australian Transport Safety Bureau (2004)

Speed is also linked to the reduction of visual ability while driving. *Figure 2.2* illustrates that at a greater speed, the driver's visual field becomes narrower, hence reducing the capability of the driver to assess potential hazards and react in time when an obstacle appears from either side of this reduced field of view (OECD/ECMT, 2006).

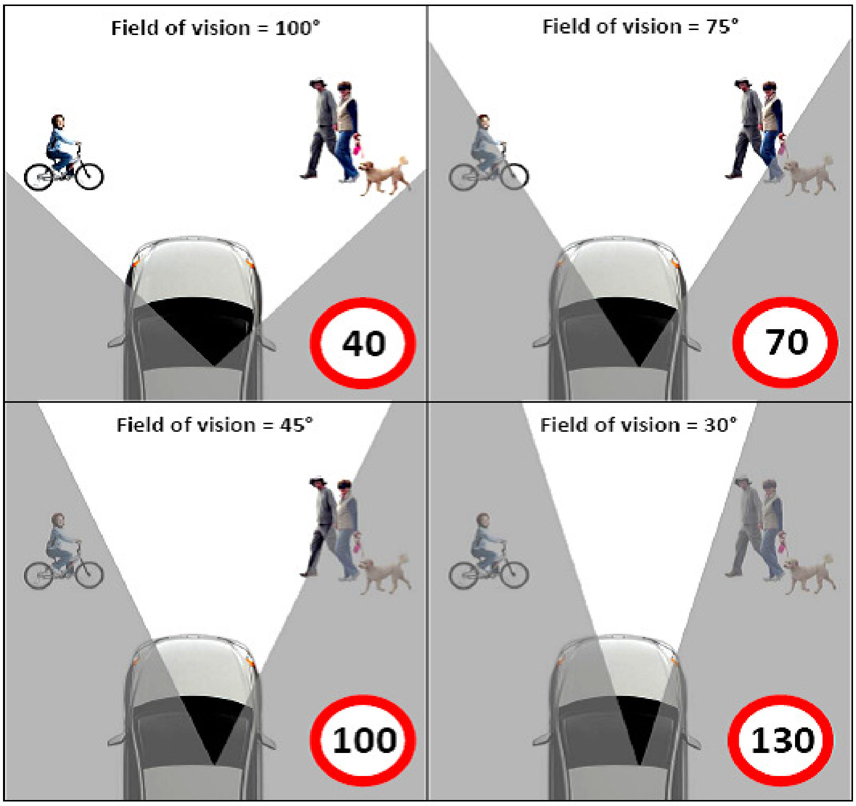


Figure 2.2 – Effect of speed on the field of vision adapted from Ministry of Transport, France (2001)

Furthermore, higher speed alters depth perception by making it more difficult for a driver to estimate distances to objects in front of them. The ability to correctly judge distances is vital for the safe execution of manoeuvres that require extra caution, such as overtaking and changing lanes. According to Marret (1994; cited in Sergerie, 2008), for each 10 km/h, a driver must be 3.75 m closer to an object in order to see it.

Researchers have attempted to correlate speed with crash frequency and severity. Though there have been varying results, one common agreement is that the number of crashes and seriousness of injury are more likely to worsen at higher speeds.

Taylor et al. (2000) concluded that a 10% increase in mean speed would result in a 21% increase in the number of crashes. Kloeden et al. (2002) found that the risk of involvement in casualty crashes is doubled for every 5 km/h increase in speed.

Nilsson (1982) found that the relationship between changes in the number of crashes and changes in speed takes the following form, which is commonly known as the "Power model":

$$\left(\frac{Crashes\ after}{Crashes\ before}\right)=\left(\frac{Speed\ after}{Speed\ before}\right)^{Exponent}$$

He proposed that the relative change in the number of injury crashes is directly proportional to the square of the relative change in speed, and rationalised that the number of severe crashes would rise at a higher rate with an increase in speed. Thus, severe injury crashes and fatal crashes were assigned larger exponent values, i.e. 3 and 4 respectively.

After some refinements to his earlier work, Nilsson (2004) produced six equations for estimating changes in the number of crashes and casualties when speed is altered. The equations are summarised in *Table 2.1* and a representation of the speed and safety relationship by way of the Power model is illustrated in *Figure 2.3*.

Table 2.1 – Summary of the Power model for change in traffic safety when speed changes from v_0 to v_1

Accidents (y)	Number of fatal accidents	$y_1 = y_0 \left(\frac{v_1}{v_0}\right)^4$
	Number of fatal and serious injury accidents	$y_1 = y_0 \left(\frac{v_1}{v_0}\right)^3$
	Number of all injury accidents	$y_1 = y_0 \left(\frac{v_1}{v_0}\right)^2$
Injured (z)	Number of fatalities	$z_1 = y_0 \left(\frac{v_1}{v_0}\right)^4 + (z_0 - y_0)\left(\frac{v_1}{v_0}\right)^8$
	Number of fatalities and seriously injured	$z_1 = y_0 \left(\frac{v_1}{v_0}\right)^3 + (z_0 - y_0)\left(\frac{v_1}{v_0}\right)^6$
	Number of all injured (including fatalities)	$z_1 = y_0 \left(\frac{v_1}{v_0}\right)^2 + (z_0 - y_0)\left(\frac{v_1}{v_0}\right)^4$

Key: v = speed, y = number of accidents, z = number of injuries, subscript 0 = “initial” and subscript 1 = “current”

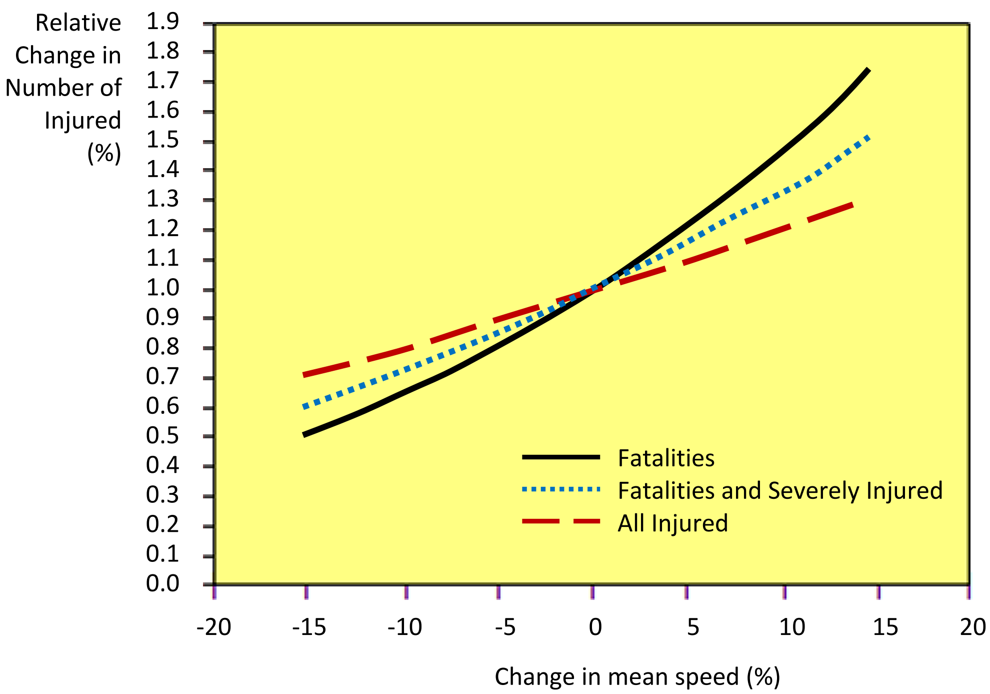


Figure 2.3 – Nilsson’s Power model reflecting the relationship between change in speed and change in the number of injured

Aarts and van Schagen (2006) in reviewing Nilsson's Power model produced estimates for the changes in crash types if the average speeds were altered by 1 km/h. Note that increases in road casualties were higher for lower speed environments, and severe crashes were more susceptible to increases in speed (see *Table 2.2*).

Table 2.2 – Expected change in crashes for different speed levels when average speed changes by 1 km/h

Reference Speed (km/h)	50	70	80	90	100	120
Injury Crashes	4.0%	2.9%	2.5%	2.2%	2.0%	1.7%
Serious Injury Crashes	6.1%	4.3%	3.8%	3.4%	3.0%	2.5%
Fatal Crashes	8.2%	5.9%	5.1%	4.5%	4.1%	3.3%

Revision to the original model was done by Elvik (2009), suggesting that the type of traffic environment moderates the effect of speed on crashes. He proposed lower estimates of the exponents for the Power model than those of Nilsson's theory, and found that the exponents were much lower on urban and residential roads than on rural roads and freeways (see *Table 2.3*).

Elvik's modified Power model provides a better representation of the effect of speed on safety in different road environments. The model is also more diverse as it allows for the estimation of changes in the number of crashes and casualties across four levels of crash types (fatal, serious, slight injuries and non-injury/property damage only), as opposed to Nilsson's Power model which has three levels – one of which combines both fatal and severe injury crashes.

Table 2.3 – Exponents for Elvik's modified Power model

	Summary estimates of exponents by traffic environment					
	Rural roads/freeways		Urban/residential roads		All roads	
Accident or injury severity	**Best estimate**	**95% CI**	**Best estimate**	**95% CI**	**Best estimate**	**95% CI**
Fatal accidents	4.1	(2.9, 5.3)	2.6	(0.3, 4.9)	3.5	(2.4, 4.6)
Fatalities	4.6	(4.0, 5.2)	3.0	(-0.5, 6.5)	4.3	(3.7, 4.9)
Serious injury accidents	2.6	(-2.7, 7.9)	1.5	(0.9, 2.1)	2.0	(1.4, 2.6)
Seriously injured road users	3.5	(0.5, 5.5)	2.0	(0.8, 3.2)	3.0	(2.0, 4.0)
Slight injury accidents	1.1	(0.0, 2.2)	1.0	(0.6, 1.4)	1.0	(0.7, 1.3)
Slightly injured road users	1.4	(0.5, 2.3)	1.1	(0.9, 1.3)	1.3	(1.1, 1.5)
Injury accidents – all	1.6	(0.9, 2.3)	1.2	(0.7, 1.7)	1.5	(1.2, 1.8)
Injured road users – all	2.2	(1.8, 2.6)	1.4	(0.4, 2.4)*	2.0	(1.6, 2.4)
PDO accidents	1.5	(0.1, 2.9)	0.8	(0.1, 1.5)	1.0	(0.5, 1.5)

CI = Confidence Interval; PDO = property damage only; * Specified informally

2.2.2 Speed limits on residential streets

Speed limits are implemented principally to regulate vehicle speeds. Speed limits vary from one road category to another, with roads in the upper hierarchy and in rural settings having higher limits.

The speed limit is the maximum speed considered safe for favourable weather and visibility. It is determined from traffic studies and engineering judgement based on experience and research. While the 85th percentile speed is a major factor in deciding on the appropriate speed limit for a given road, traffic engineers also consider other factors such as adjacent land-use and developments, accident experience, roadway characteristics and pedestrian/cyclist activity.

It is believed that lower speed limits would result in lower mean speeds, and consequently, reductions in the number of crashes and road trauma. There has been a lot of research done to relate the impact of changing speed limits on safety, and the findings are mostly in agreement with this. In fact, Nilsson

(1982, 2004) produced his Power model from studying the effects of lowering and increasing speed limits on crash frequency and severity.

Elvik et al. (2004) revealed that speed limits actually have an influence on the mean speed of traffic, as shown in *Figure 2.4*. On average, the change in mean speed resulting from a change in speed limit is approximately 25% of the change in speed limit, meaning that when the speed limit is lowered by 10 km/h, the mean speed will decrease by 2.5 km/h.

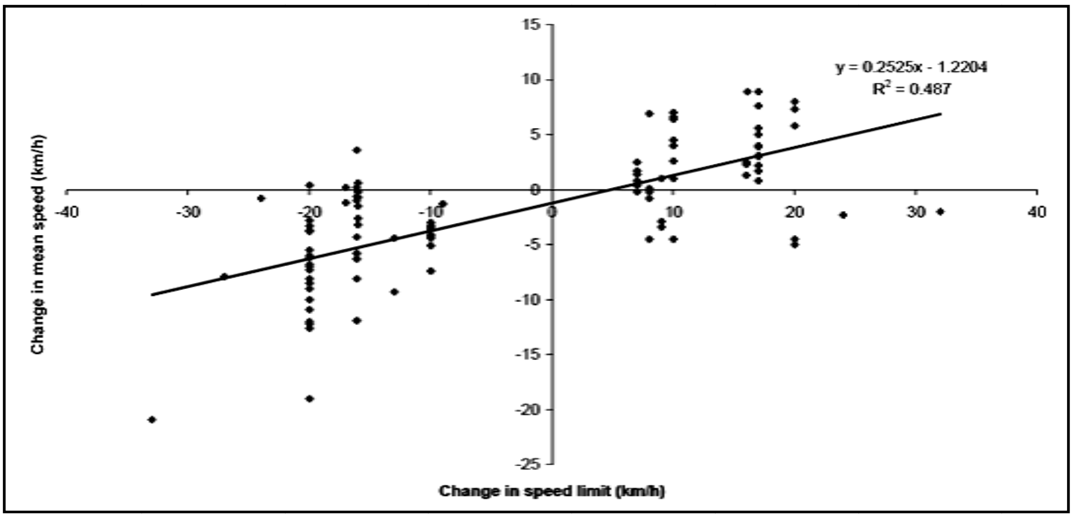


Figure 2.4 – Relationship between change in speed limit and change in mean speed (source: Elvik et al., 2004)

Elvik et al.'s finding echoed an earlier study by Finch et al. (1994), who obtained a relationship between the change in mean speed (ΔS) and the change in the posted speed limit (ΔL) as follows:

$$\Delta S = 0.24 \Delta L \tag{2.1}$$

In the same study by Finch et al., a meta-analysis of crash studies was conducted using data from Finland, Denmark, Sweden, Germany, Switzerland and the United States of America. It was found that crashes change by about 5% for every 1 mph (1.6 km/h) change in the mean speed, meaning that if mean speed was to drop by 1 mph, the number of crashes would drop by 5% (see *Figure 2.5*).

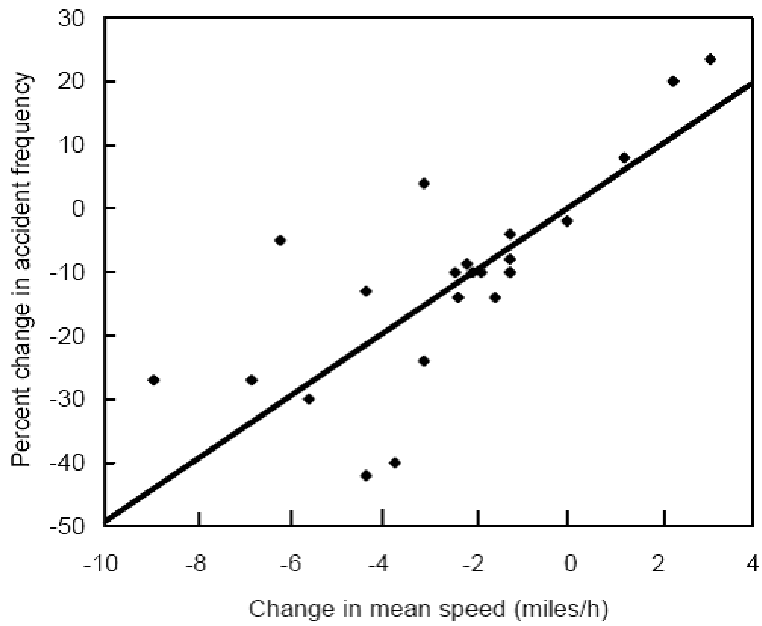


Figure 2.5 – Relationship between mean speed and accidents (Finch et al., 1994)

The relationship between the change in accidents (ΔA) and the change in mean speed (ΔS) by Finch et al. is given by:

$$\Delta A = 4.92 \Delta S \quad (2.2)$$

Elvik and Vaa (2004), in their review of various studies related to speed limits, disclosed that by reducing or introducing speed limits, an overall reduction in crash numbers of 13% was attained. Apart from that, they found that lowering speed limits from 110 – 115 km/h to 88 – 97 km/h could result in reductions in fatality crashes and injury crashes by up to 54% and 6% respectively.

The outcome from reducing speed limits on urban roads, particularly arterials and local streets, may not necessarily mirror those effects reported in previously mentioned studies, which tend to focus mainly on rural and motorway speed limits.

The risk of crashes is high on major roads (such as arterials) and minor roads (such as local streets) due to the large number of access points such as driveways. In New Zealand, there was an average 10 fatal crashes and 460 injury crashes per year involving a vehicle entering or exiting a driveway in an urban area between 1996 and 1998 (Patterson et al., 2000).

The Australian experience in reducing the default urban speed limit (DUSL) from 60 km/h to 50 km/h since 1997 provides us with a better understanding of how changes to the speed limit ultimately impacts road safety in urban areas.

Archer et al. (2008) inferred from a number of studies conducted on the safety impact of the new DUSL that crash frequency and severity were considerably lower after its implementation, in spite of the travel speeds experiencing relatively small decreases. Casualty crashes dropped by 8% in Queensland (Walsh & Smith, 1999) and 12% in Victoria (Horeau et al., 2006), while South Australia experienced a 19.8% reduction (Kloeden et al., 2004).

It was also noted that pedestrian safety improved remarkably as a result of the new DUSL, with Horeau & Newstead (2004) reporting a 51% net reduction in pedestrian-related crashes in Western Australia, while in Victoria, reductions of about 25% – 40% were recorded for fatal and serious injury crashes involving pedestrians (Hoareau et al., 2006).

Research has thus far shown that there are some major safety benefits to be reaped from lowering speed limits. Special attention should be drawn to the 50 km/h urban speed limit applied to include residential streets. As previously stated, this speed limit may be too high for such roads, given their function and characteristics.

Several European countries have acknowledged the need to reduce the speed limit for residential streets to 30 km/h, and have seen success from the implementation of what they commonly call “30 km/h zones” or “Zone 30”.

A study of 679 streets in Denmark with the 30 km/h speed limit showed that the number of crashes in the inner areas, i.e. parts of the streets regulated by the speed limit sign, dropped by almost 25%, while the number of casualties fell by nearly 56% (Engel & Thomsen, 1992).

Webster & Mackie (1996), upon studying 20 mph (32 km/h) zones in England, Wales and Scotland, reported that the annual crash rate dipped by 60%, while child-related and cyclist-related crashes decreased by 67% and 29% respectively, as a result of the lower speed initiative. Furthermore, average speeds were down by 9 mph (14.5 km/h) and traffic volumes shrunk by 27%.

In the Netherlands, 30 km/h zones were just as successful in improving road safety in neighbourhoods, with the number of hospital admission crashes decreasing by 27% (Steenaert et al., 2004; cited in SWOV, 2006), and the number of fatalities and casualties per km of road falling by 10% and 60% respectively (Wegman et al., 2006; cited in SWOV, 2006).

It should be noted that these low speed zones incorporate traffic calming schemes that appear to be reducing vehicle speeds to the desired levels. Therefore, the safety improvements are partly due to the accompanying speed control measures. Having a 30 km/h advisory speed sign on its own may not result in the desired safety effects.

The drop in the number of road trauma cases as a result of low speed initiatives can be attributed to the reduction of the travel speed, which heightens not only driver alertness but also increases the likelihood of a driver avoiding collision, as the driver has more time and space to activate the brake pedal or perform any other defensive driving manoeuvres.

Under circumstances when a collision is inevitable, a low travelling speed would mean a low impact speed, which could turn out to be life-saving. The risk of a pedestrian dying as a result of being hit by a car moving at 50 km/h is twice as high as the risk at 40 km/h and more than five times higher than the risk at 30 km/h (Rosen & Sander, 2009).

Other benefits of converting residential streets into low speed zones include improvements to the quality of life, as slower traffic might result in reduced noise and exhaust emissions, and streets become more liveable with less people being threatened by fast-moving traffic and more people walking and cycling (T&E, 2001).

2.2.3 *Altering driver behaviour to achieve safer streets*

When a lower speed limit is planned for a residential area, the next step is to get its residents to support the new speed regulation and drivers, who are residents themselves (residing along the affected streets or other streets), to adhere to it. A simple, low-cost approach is through the dissemination of information about the need to reduce speed limits and the benefits from its implementation. While it is not likely that residents would turn down efforts to enhance the safety of their streets, there is always a possibility of them exceeding the speed limit, intentionally or unintentionally.

Predicting how a driver will respond to changes in the speed limit is not an easy task. But, there is a need to understand how their minds work or what inspires them to make decisions when driving.

A driver is influenced by an array of internal and external factors when driving a vehicle on the road. The World Health Organisation lists a total of 32 variables that are believed to affect a driver's choice of speed (see *Table 2.4*). These variables represent three main contributory factors: driver related factors, road and vehicle factors, and traffic and environment factors.

Table 2.4 – Factors affecting choice of speed among drivers (WHO, 2004)

Driver Related Factors	Road and Vehicle Factors	Traffic and Environment Factors
Age	**Road**	**Traffic**
Sex	Width	Density
Reaction time	Gradient	Composition
Attitudes	Alignment	Prevailing speed
Thrill-seeking	Surroundings	**Environment**
Risk acceptance	Layout	Weather
Hazard perception	Markings	Surface condition
Alcohol level	Surface quality	Natural light
Ownership of vehicle	**Vehicle**	Road lighting
Circumstances of journey	Type	Signs
Occupancy of vehicle	Power/weight ratio	Speed limit
	Maximum speed	Enforcement
	Comfort	

Shinar (2007) explains that drivers' choice of speed is governed by individual differences and motivational factors. Age, gender, education and income have diverse effects on speed choice. Men are more likely to speed than women (Jonah et al., 2001) and younger drivers are more likely to speed than older drivers (Horberry et al., 2004). Interestingly, Shinar et al. (2001) found that drivers with higher education and income levels are more likely to exceed speed limits, owing to their familiarity with conflicting arguments and data about speed-crash relationship, and ability to pay stiff penalties for speed violation.

The theory of planned behaviour (Ajzen, 1991) explains that the formulation of our intentions to commit any behaviour is on the basis of our attitude, the subjective norm and the perceived control. Based on this theory, De Pelsmacker & Janssens (2007) developed a model of speed choice behaviour from a survey involving Belgian drivers. The model suggests that the intention to speed is determined mainly by the habit of speeding and the attitude towards speeding, but not much by the affective attitude towards speed limits (refer to *Figure 2.6*).

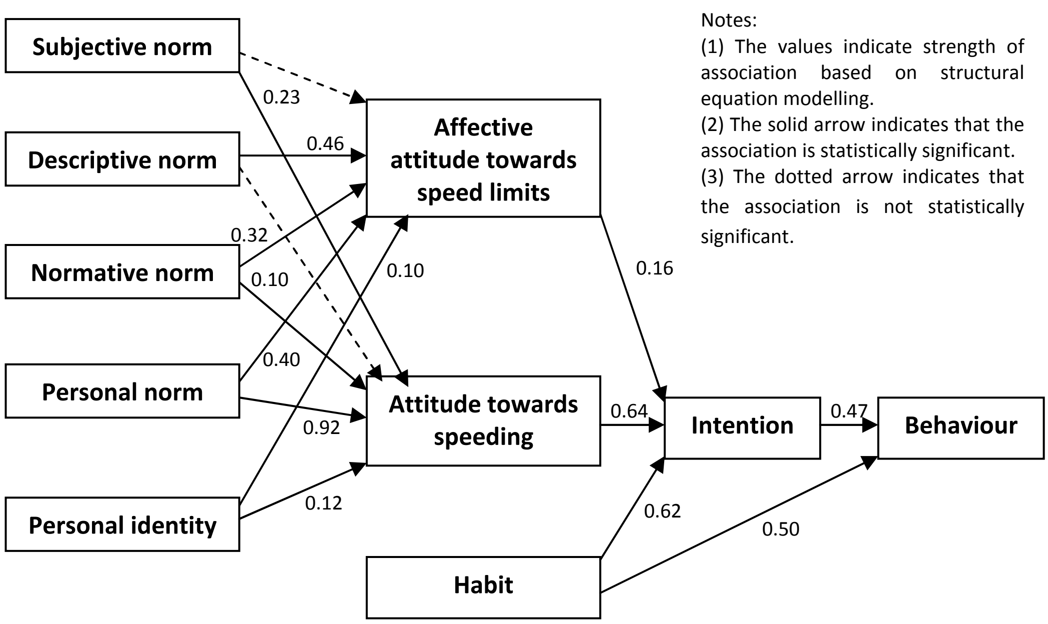


Figure 2.6 – The model of speed choice behaviour showing strength of association between relevant concepts

The variables used in De Pelsmacker & Janssens' study are explained in *Table 2.5*, while *Table 2.6* sums up the influence level of variables that were found to be significantly associated with driver behaviour. Habit seems to have a major effect on driver actions, with most drivers having a strong propensity to agree that they frequently drive over the speed limit, speed without thinking and drive fast because they do it all the time.

Table 2.5 – Explanation of the variables used in De Pelsmacker & Janssens' study

Variables	**Description**
Affective attitude towards speed limits	What I feel about respecting speed limits *(i.e. nervous / fun / annoyed)*
Affective attitude towards speeding	What I feel about speeding *(i.e. happy / excited)*
Attitude towards speeding	What I think about speeding *(i.e. it is a reckless behaviour / it makes me mad seeing people speed)*
Attitude towards speed controls	What speed controls I think might deter speeding *(i.e. higher fines / more speed cameras)*
Attitude towards accidents	What I think about safety as a result of respecting speed limits *(i.e. lowers chance of accident / enables me to stop faster in case of emergency)*
Subjective norm	What I think other people think about me with regards to speed limits *(i.e. my best friend/child/spouse thinks I may never exceed the speed limit)*
Descriptive norm	What I think other people would do if I respect the speed limit *(i.e. people will overtake me / drive closely to my car)*
Normative norm	What I would do, seeing as other people are doing it (i.e. my speed is just like the speed of other drivers)
Personal norm	What I think I should do based on my personal values *(i.e. I feel bad after speeding / I have a strong obligation not to exceed the speed limit)*
Personal identity	What I think about my own driving skills *(i.e. I know what to do in emergencies / I am better than the average driver)*
Habit	What I usually do when driving *(i.e. I frequently drive faster than the speed limit / I drive fast because I do it all the time)*
Intention	What I would do in future *(i.e. I will obey the speed limit the next time / I will continue driving fast)*

Table 2.6 – Total effects of variables considered and their speeding behaviour in order of importance

Variables	Size of Effect (significance)
Habit	0.787 (<0.001)
Intention	0.471 (<0.001)
Personal norm	0.307 (<0.001)
Attitude towards speeding	0.300(<0.001)
Affective attitude towards speed limits	0.077 (0.027)
Subjective norm	0.074(<0.001)
Normative norm	0.057 (0.024)
Personal identity	0.042 (0.023)
Descriptive norm	0.031 (0.151)

Road safety surveys in the Netherlands revealed that there has been a drop in driver compliance with speed limits over time and as expected, drivers were less inclined to obey speed limits in lower speed environments. About 40% of the drivers adhered to the 50 km/h speed limit and close to 30% adhered to the 30 km/h speed limit. It was also found that drivers in these environments exceeded speed limits mainly to adapt to traffic and out of haste. Drivers also recognised that they had exceeded the limits without actually realising it and did it for sheer enjoyment (SWOV, 2010).

If a street is to be given a 30 km/h speed limit, it is important that the street should look like a 30 km/h street. Coupled with the fact that speeding is instinctively habitual or intentional, the need to incorporate speed reducing elements in the design of a 30 km/h street is vital not only to present a "drive slow and carefully through our street" image, but to modify driver behaviour by restricting speeding actions through physical alterations to the street.

2.3 Review of neighbourhood traffic management

The adverse effects of speeding in neighbourhoods can be narrowed down to issues pertaining to safety and liveability. Fast moving traffic elevates the risk of crashes and perceptions that a street is not safe for walking, cycling or playing, and emits exterior sounds that may disrupt the tranquillity of neighbourhoods.

In order to allay the problem of speeding, the factors influencing speed choice need to be understood before speed management programs are implemented. Driver behaviour modification, particularly in controlling the speeding habit or intention to speed, can be successfully done through alternative street designs that restrain drivers from driving too fast.

Traditionally, traffic enforcement programs and speed signs were used to slow traffic but they had minimal effect in mitigating speeding problems in neighbourhoods. Subsequently, speed management techniques aimed at altering driver behaviour through innovative street designs were introduced and were proven to be effective. One such technique is traffic calming, which relies on the concept of using physical and visual devices to persuade motorists to slow down.

The Institute of Transportation Engineers (Ewing, 1999) defines traffic calming as follows:

> *"Traffic calming involves changes in street alignment, installation of barriers, and other physical measures to reduce traffic speeds and/or cut-through volumes, in the interest of street safety, liveability, and other public purposes."*

This definition provides a solid explanation of traffic calming as it aptly describes the general method, purpose and benefit. However, one tends to wonder why this updated definition does not include the notion of "altering driver behaviour" as defined by Lockwood (1997). Perhaps, the former is more workable in the sense that it does not depend on changing behaviour, which may be a sensitive subject to some.

The physical devices used in traffic calming can be divided into two broad categories: vertical deflections and horizontal deflections.

Vertical deflections are raised segments that force drivers to slow down in order to minimise unpleasant bumping or vibrating sensations. Examples of vertical deflections are speed humps, speed tables, speed cushions, raised intersections, rumble strips and textured surfaces (cobbled or interlocking paving blocks).

Horizontal deflections are lateral shifts in the roadway that create non-linear driving paths, thus encouraging slow and safe movement through the shifts. Horizontal deflections also include constrictions of the roadway which cause drivers to lower their speeds in order to avoid encroaching into the path of oncoming traffic or to stop and give way when the constriction permits only one vehicle at a time. Examples include mid-block narrowings, angled slow points, chicanes and central islands.

Non-physical measures such as centreline and edgeline lane striping, optical speed bars, signage, stop signs and turn restrictions are also regarded as traffic calming tools, but studies have shown that these measures have little or no effect in reducing traffic speeds and volumes, but are more effective when combined with physical measures (Ewing & Brown, 2009).

Traffic calming is commonly applied as a spot treatment to a single street, or as an area-wide scheme covering a cluster of streets. The latter may be termed Local Area Traffic Management (LATM).

Used regularly in Australia and New Zealand, LATM considers neighbourhood traffic-related problems and their solutions in the context of the local area, which is defined as an area consisting of only local streets and collectors. It necessitates that all physical measures be treated as a series of interrelated devices rather than as individual treatments (Austroads, 2008).

2.3.1 The beginnings of traffic calming

Looking back at history, it was the residents who first initiated measures to slow down vehicles on their residential streets. In the late 1960s, residents of Delft in the Netherlands decided to take action into their own hands by placing paving stones on their streets to form a meandering path so that speeding motorists who frequently passed through their neighbourhood would slow down (Kjemtrup & Herrstedt, 1992; Stillings & Lockwood, 2001). Traffic did slow down, but more importantly, their action gave birth to what is now known as "traffic calming".

Dutch officials recognised this public intervention as an effective speed reduction strategy and it inspired them to create and legalise the "*woonerf*". A *woonerf* is a Dutch word that simply means "street for living". A *woonerf* is characterised by streets that are shared by non-motorised and motorised road users. It was established that non-motorised users, predominantly pedestrians, are at the apex of the hierarchy and motorists are 'intruders' who are required to drive at very low speeds. *Woonerven* (plural of *woonerf*) are further typified by the non-existence of curbs and sidewalks and the placement of trees, planters and other obstacles on the street. This is to present *woonerven* as public spaces intended for local residents (Zeeger et al., 2002).

The idea of physically modifying streets to slow down vehicles soon spread to other countries in Europe. Denmark amended its Road Traffic Act in 1976 to give importance to playing and walking. Thus, the new regulations allowed the establishment of roads where motorists were considered as secondary road users and had to yield to pedestrians – the primary road users. The Danish equivalents to the *woonerven* were called "Section 40 areas" or "shared areas". Next came the establishment of "silent roads", which were 30 km/h zones supported by the use of physical speed control devices (Kjemtrup & Herrdstedt, 1992).

Germany experimented with this idea in the late 1970s and it was the Germans who came up with the term "traffic calming", a translation of what they called *verkehrsberuhigung*. They went on to implement area-wide traffic calming schemes and conducted extensive studies that turned out to be advantageous, leading to a warm global reception towards this idea (Ewing, 1999). In the 1980s, the “Tempo 30” zones were introduced, with neighbourhoods converted into 30 km/h speed zones and traffic calming devices used extensively. Tempo 30 zones were soon adopted by countries across Europe.

The traffic calming experience in United Kingdom dates back to the early 1960s when the Buchanan Report (Buchanan, 1963) acknowledged that the increase in traffic was threatening the quality of urban living. Consequently, much emphasis was given to controlling traffic volumes and virtually none to controlling speeds. The Urban Safety Project, which prominently featured traffic volume control measures, was launched in 1982 to reduce traffic accidents, but received criticism over its modest impact on crash rates. By 1990, the application of speed control measures started to gain status. With the 1992 Traffic Calming Act and 1993 Traffic Calming Regulations in place, a wider range of traffic calming tools were used in the design of safer streets (Ewing, 1999).

The beginnings of traffic calming in Australia were similar to that in the UK, owing to the influence of British town planning. Initially, the idea of local traffic restraint was adopted as an environmental improvement strategy. That soon changed in the late 1970s when the Australian Road Research Board (ARRB) started to document the safety motivation for local traffic restraints and to promote the concept of “environment of care” in local traffic management and street design. Soon after, the Australian area-wide traffic calming schemes or what they call LATM programs were implemented throughout Australia (Brindle, 1992).

The first reported traffic restraint measures reported in the United States were in the late 1940s or early 1950s when street closures and traffic diverters were employed to treat problem streets. But it was not until the 1970s that full-scale traffic management plans covering larger areas were implemented (Ewing, 1999).

2.3.2 *Benefits of traffic calming*

Some of the earliest studies on the effects of traffic calming were for the most part centred on speed, crash and volume reductions. Crashes tended to decrease with the decline in magnitudes of vehicular speed and traffic. Goos (1986), from his study on the safety impact of traffic calming projects in Eindhoven and Rijswijk, discerned that a more than 80% reduction in injury-related crashes was achieved, owing to reductions of motorised traffic (by 16% to 25%) and average speed (by 22% to 40%) brought about by traffic calming.

Reductions in average and 85th percentile speeds are the most significant impact of traffic calming. An area-wide traffic calming program implemented in Moabit (Germany) produced astonishing results. The average traffic speed was halved to 19.3 km/h and the 85th percentile speed dropped from 49.9 km/h to 24.1 km/h (Pharoah & Russell, 1989).

The change in speed varies according to the type of calming device installed. Studies in the US showed that speed reductions were highest for vertical deflections, with the exception of raised intersections, which produced a marginal reduction (Ewing & Brown, 2009).

Other studies that reported big drops in speed resulting from the installation of vertical deflections were by Ponnaluri & Groce (2005), reporting that speed humps had reduced 85th percentile speeds by up to 29%, and Johnson & Nedzesky (2004), finding that speed cushions cut down average crossing speeds to 16.3 km/h.

Minnema (2006) evaluated the effectiveness of various traffic calming devices in New Zealand and reported considerable reductions of more than 10 km/h in 85th percentile speeds for road cushions, roundabouts and raised tables. It was also found that narrowing carriageways from 11 m to 6 m produced large speed reductions. *Table 2.7* summarises these findings.

Table 2.7 – Impact of traffic calming devices on speed in New Zealand

Device	**Change in Speed**[a]	
	Mean (km/h)	85th Percentile (km/h)
Road Cushion (100 mm)	-12.8	-14.1
Road Cushion (75 mm)	-8.2 to -14.4	-8.6 to -16.2
Perimeter Threshold[b]	-10.4 to -14.0	-12.6 to -20.0
Raised Table	-8.8	-10.1
Road Hump (Watts profile)	-6.0	-7.0
Roundabout	-12.2	-12.6
Median Island	-2.8	-3.3
Carriageway Narrowing (11 m to 6 m)	-9.8	-11.1
Carriageway Narrowing (11 m to 8 m)	-2.8	-2.1

a: Based on before-and-after studies. For after studies, speeds were measured between devices

b: Results may be heavily influenced by raised tables which were used in-conjunction

Another New Zealand study by Mao and Koorey (2011) reported speed reductions across a speed hump (8%), a speed table (6%), a one-lane pinch point (3%) and a two-lane pinch point (2%).

Improvement in safety on streets is largely due to the decrease in traffic speed. Kloeden et al. (1998) described the influence of speed on traffic safety most vividly, claiming that each 1 mph (1.6 km/h) of traffic speed reduction typically reduces vehicle collisions by 5% and fatalities by an even greater amount. A study on the safety benefits of traffic calming implemented in the Greater Vancouver area revealed an average of 40% reduction in collision frequency and a 38% reduction in annual claim costs (Zein et al., 1997).

Pedestrian-related crashes occurring on local streets are a chief concern as there is a strong likelihood of death and serious injury to a pedestrian as a result of getting hit by a speeding vehicle. Traffic calming reduces vehicle speeds which in turn reduces the chances of collision and increases the chances of survival if a collision was to occur. A study in Gothenburg (Sweden) showed that as a result of traffic calming initiatives, the number of crashes involving pedestrians was reduced by 41% (Huzevka, 2005).

When cut-through traffic intrudes upon the local street system, residents may experience safety and environmental problems. Overall and cut-through traffic have been significantly reduced by various traffic calming methods. In Austin, Texas, speed humps were found to have reduced daily traffic by as much as 39%, while diagonal diverters resulted in an up to 82% reduction in cut-through traffic (City of Austin, 1996).

Street closures have also been employed as traffic calming techniques to deter traffic. Ewing & Brown (2009) reported that half-closures and full-closures produced reductions in daily traffic volumes. *Table 2.8* summarises Ewing's evaluation of traffic calming devices in the US.

Table 2.8 – Impact of traffic calming devices in United States

Device	**Average Change**	
	85^{th} Percentile Speed, in km/h [%]	Daily Traffic Volume, in veh/day [%]
Humps, 12 ft (3.7 m)	-12.6 [-22]	-335 [-18]
Humps, 14 ft (4.3 m)	-12.4 [-23]	-529 [-22]
Lumps	-14.3 [-25]	-165 [-7]
Tables, 22 ft (6.7 m)	-11.7 [-20]	-415 [-12]
Longer Tables	-5.8 [-10]	n/a
Raised Intersections	-0.5 [-1]	n/a
Mini-circles	-6.3 [-11]	-293 [-5]
Narrowings	-4.2 [-4]	-263 [-10]
One-lane Slow Points	-7.7 [-14]	-392 [-20]
Full Closures	n/a	-671 [-44]
Half Closures	-9.7 [-19]	-1611 [-42]
Diagonal Diverters	-2.3 [-4]	-501 [-35]

With calls for sustainable travel in current times, traffic calming may be able to change the way people travel by promoting walking and cycling, and reducing their dependence on automobiles. Litman (1999) revealed that if per household non-motorised trips currently averaged at 1.8 per day, comprehensive traffic calming could increase this to 2.0 – 2.2, and reduce 0.1 – 0.2 motor vehicle trips per day.

The reduction of traffic speed and volumes on local streets might induce less traffic noise and exhaust emissions, resulting in more tranquil and healthy environments for living. Studies have shown that for urban areas, a 6 mph (9.7 km/h) reduction in speed can cut noise levels up to 40% (Mitchell, 2009), while Pharoah (1989) found that lower vehicle emissions of carbon monoxide (-17%), hydrocarbons (-10%) and nitrogen oxides (-32%) were achieved by taming “aggressive” drivers.

Traffic calming also has favourable social impacts. Lennard & Lennard (1995) wrote that traffic calming helps make public streets lively and friendly, encourages community interaction, and attracts customers to commercial areas. Vibrant streets, teeming with residents going about their daily activities appear to repel criminal activities. Burrington & Heart (1998) found that traffic calming reduced crime in Ohio neighbourhoods by 25 – 50%.

2.3.3 Criticisms of traffic calming

In the past, there has been criticism towards traffic calming coming from emergency response providers who argue that calming devices impede emergency services. Vertical deflections, particularly speed humps, have been singled out as devices that cause major hindrance to emergency vehicles.

Montgomery County Fire and Rescue Commission (1997) conducted their own study to expose the influence of calming devices on the emergency response times of four types of emergency vehicles, i.e. fire engine, ladder truck, aerial tower truck and ambulance. They concluded that speed humps incur between 2.8 to 7.3 seconds delay while maintaining a constant speed of 25 mph (40.2 km/h). In addition to that, the four vehicles averaged slightly less than 20 mph (32.1 km/h), which is nearly half the response cruising speed of 35 - 40 mph (56.3 - 64.4 km/h) typically attained on unimpeded roads.

These findings supported an earlier study by Coleman (1996) which found that fire vehicles in Portland experienced delays of 0.0 – 9.2 seconds per 22 ft (6.7 m) speed bump and 1.0 – 9.4 seconds per 14 ft (4.3 m) speed bump.

Calongne (2003) highlighted that deflection devices require emergency drivers to slow down to almost a stop, hence rendering greater risks of losing lives of victims being transported. Calongne went on to claim that response times of less than 7 minutes can save 30% of sudden cardiac arrest (SCA) victims. Conversely, an average response time of 12 minutes only saves 2% of SCA victims. However, it should be noted that an emergency vehicle crossing a speed hump may only be delayed by about 5 seconds, thus the vehicle will have to endure 60 speed humps for the response time to increase by 5 minutes!

Another concern over traffic calming is the noise emitted as a result of vehicles traversing vertical deflections. Abbott et al. (1997) noted that speed humps and cushions give rise to vehicle body noise (e.g. body rattle, suspension noise, etc.) which leads to noise disturbance. This was evident for traffic with considerable proportions of large commercial vehicles running over wide speed cushions and flat-top road humps. Despite running at low speeds, noise levels increased by 6.3 dBA and 7.9 dBA respectively for wide speed cushions and flat-top road humps.

Contradictory findings of the impact of traffic calming on air quality have also been reported. While it is generally agreed that traffic calming reduces traffic volume and speeds, thus reducing traffic air pollution, some microsite studies show otherwise. Boulter & Webster (1997) revealed that increases in carbon monoxide (CO) and hydrocarbons (HC) of 70 - 80% and 70 - 100% respectively were recorded for traffic calming schemes with road humps spaced at 75 metres.

A further study by Boulter & Hickman in 2001 claimed that there were increases in CO, HC and nitrogen oxides (NO_x) of 59%, 54% and 8% respectively for petrol catalyst vehicles after traffic calming schemes were implemented. The study also concluded that speed humps created the largest increase in pollutants of all the calming devices tested.

There is also concern about cyclist safety if the design of obstructive and deflective calming devices does not provide safe passages for cyclists. Such designs limit the safe space required between cyclists and vehicular traffic during travel. Video surveys taken at a road section constricted by central islands, chicanes and pinch-points in the UK revealed that at least 70% of drivers attempted to overtake cyclists within or close to a 3.5 m narrowing. From concurrent interviews with cyclists, it was found that cyclists were threatened by the closeness of vehicles at these narrowings, particularly at points where the roadway began to narrow (DETR, 1997).

A study in New Zealand showed that when motorists and cyclists approached a 4.5 m wide pinch-point simultaneously, either the motorist or the cyclist had given way 57% of the time. It was found that 3 out of 10 motorists did not yield to cyclists. In fact, it was the cyclists who yielded to motorists. Also, cyclists chose to avoid using the narrowed road section by using the footpath 8% of the time (Chai et al., 2011).

2.3.4 Public acceptance of traffic calming

Acceptance by the local community is seen as the key to successful traffic calming. Therefore, public involvement in the preparation, design and implementation of traffic calming schemes is essential. By involving the public, practitioners can benefit from its feedback, and a deeper understanding and acceptance of a particular scheme can be promoted (Pharoah, 1992).

There has been a generally mixed reception towards traffic calming since its inception. Pharoah & Russell (1989) noted that there was initial resistance towards an area-wide traffic calming scheme in Buxtehude, Germany, where 46% of car drivers and 49% of residents opposed the scheme. However, three years after the implementation of the scheme, resistance dropped to 33% and 24% respectively. Interestingly, the approval rating among car drivers increased by 13% despite drivers having to slow down as a result of the lowering of speed limits and also navigate their cars through unconventionally designed streets that featured narrowings, on-street parking bays, and entrance and junction treatments.

Public acceptance of traffic calming is believed to be influenced by the public's reasoning and personal experience with regards to its benefits. According to a study by Ballard (1998) residents were mostly receptive towards the installation of speed humps. 75% of the respondents were in favour of these devices, with 67% of them recognising that the speed humps had effectively slowed traffic and 5% thought that the humps had improved safety.

Comfort is also seen as a critical factor in public acceptance of traffic calming devices. Marek & Walgren (1998) found that the speed table received a higher approval rating than the speed hump, regardless of the public acknowledging that the speed hump was more effective than the speed table in reducing traffic speeds and volumes, and enhancing safety.

Smith et al. (2002) also sought public reaction to the idea of having vertical deflections on their streets by installing removable speed humps and speed tables. Generally, the residents were supportive of the use of these vertical deflections and had perceived reduced speeds but no change in volumes, and increased safety and driver attention. However, most respondents indicated they had no preference, when it came to choosing between the speed hump and the speed table. This was probably due to their opinion that the speed hump/table was less 'punishing' than the speed bump, which they were more familiar with.

Drivers' acceptance of vertical deflections would naturally be lower than of horizontal deflections or non-physical traffic calming measures, given that drivers experience some level of discomfort when traversing the former. Du et al. (2003) found that drivers and residents viewed horizontal deflections more positively than vertical deflections. Support among drivers for medians, chokers and chicanes was about 70%, while for speed humps it was about 50%. Residents were just as unsatisfied with speed humps as drivers were. Many of the residents objected the installation of speed humps mainly due to its appearance, and the perception of increased noise and air pollution produced across the humps.

As seen historically, there have been more proponents of traffic calming initiatives than those who oppose. It is therefore highly unlikely that public objections will gain momentum in the future. Continuous improvements to the design of calming devices in order to effectively reduce speeds without sacrificing comfort is vital, and so is regular exchange of opinions between the public and practitioners before and after implementing speed control initiatives. This will help keep traffic calming relevant, tolerable and appreciated for many more decades to come.

2.3.5 Alternative speed management techniques

Apart from the previously mentioned physical and non-physical traffic calming measures, vehicle speeds may also be managed through urban design ideas such as the "shared space" concept, and in-vehicle speed regulators such as speed limiters and the Intelligent Speed Adaptation (ISA) system.

Shared space is a design concept that is intended to promote streets and other public areas as spaces shared by both motorised and non-motorised travellers. This is achieved by reducing the dominance of motor vehicles and encouraging drivers to be more accommodating towards pedestrians. An interesting aspect of shared spaces is that users are encouraged to share the space rather than adhere to clearly defined regulations that are typical of those found on conventional streets. Shared space streets are characterised by minimal or no demarcations between vehicles and pedestrians (i.e. guardrails, curbs, pavement markings, traffic signs and traffic signals) and speed limits preferably less than 25 km/h (Department for Transport, 2011).

The "shared space" concept is not intended to succeed traffic calming. In fact, traffic calming may be employed in shared spaces to keep vehicle speeds within the desired speed limit. Furthermore, shared spaces are only suited for areas where pedestrian activity is high, such as town squares, tourist attractions, shopping malls and junctions. Traffic calming will also be needed if 30 km/h and 40 km/h speed zones are implemented in neighbourhoods.

Speed limiters are devices fitted in vehicles to limit the top speed of the vehicles. These devices either restrict the engine's fuel injection or exerts pedal resistance (i.e. counter-force of the active accelerator pedal) whenever the pre-determined maximum speed is exceeded (Verhalyi & Makinen, 2001).

Speed limiters are mandatory for buses and heavy goods vehicles in some countries, but universally non-mandatory for passenger cars. However, some car manufacturers include speed limiters as an added feature. These may be programmable (drivers can actuate and override the speed limiter) or fixed (usually for high-powered and electric cars).

Programmable speed limiters may be useful when safety-conscious drivers travel through 30 km/h or 40 km/h speed zones and shared space streets. This will certainly require manual activation and deactivation of the speed limiter by the driver, which could be a hassle when travelling along road networks with various speed limits.

Thus, Intelligent Speed Adaptation (ISA) is an upgrade to the speed limiter. ISA is a set of systems that supports drivers in helping them comply with speed limits. It uses information of the position of the vehicle in relation to the speed limit at that particular location.

ISA can be implemented as an "advisory" tool that simply reminds the driver of the prevailing speed limits and exerts no control over the vehicle. ISA may alternatively function as a "voluntary" tool that limits the vehicle speed to the prevailing speed limit, but the driver is allowed to deactivate the system, or a "mandatory" tool that gives the system full control of the speed (Jamson et al., 2006).

Studies show that ISA had a calming effect on drivers' driving style (Lahrmann et al., 2001; Bessling & van Boxtel, 2001) and improved drivers' attention (Almqvist & Nygard, 1997; Lahrmann et al., 2001; Biding & Lind, 2002).

General acceptance of ISA is essential in making ISA mandatory for all classes of vehicles. Carsten (2002) opined that the uptake of ISA will likely be low without strong public support and political backing. Public surveys reveal that some drivers felt that ISA took away their freedom as a result of loss of control (Bessling & van Boxtel, 2001), while others reported increases in levels of frustration and annoyance (Paatalo et al., 2001; Biding and Lind, 2002).

Traffic calming will remain as a speed management technique of choice unless people are more receptive to the in-vehicle speed regulators and strong political support is garnered to make speed limiters or ISA mandatory. Studies show that proponents and opponents of this new technology are evenly split (MORI, 2001). Interestingly, 58% of drivers supported the idea of having speed limiters mandatory for cars in 30 mph (48 km/h) zones if this meant that speed humps are to be removed (MORI 2002).

2.4 Estimating vehicle speeds

Speed is one of the most important factors considered in the design of roads. A critical goal of geometric road design is to ensure that drivers are able to safely manoeuvre their vehicles along a road in any geographic location, and particularly when topological conditions make it more difficult for drivers to control their vehicles than when driving on flat, straight roads.

The geometry of a road needs to be designed appropriately so that drivers can maintain safe operating speeds and suitably alter their speeds when negotiating horizontal and vertical alignments. The initial step in the design process is to select an appropriate design speed. The design speed sets the general standard of the road and the design scope for other design parameters, such as sight distances, curve radius, superelevation and grades.

Correlating speed with its influencing factors through statistical analysis is a major step forward in procuring knowledge on the level of effect these factors have on speed. It is also a way of studying driver behaviour. While most speed models attempt to relate speed with roadway characteristics, there have been models produced to gauge speed choice based on individual and vehicle factors.

Although the outcomes from these models may vary from each other due to sampling differences, they do provide some guidance to practitioners in the planning and design of roads. The following section presents some examples of speed models.

2.4.1 Speed prediction models

While most speed models focused on high-speed rural roads, Fitzpatrick et al. (2000) shifted attention to four-lane suburban arterials, obtaining linear models to explain factors which influence speed on horizontal curves and straight sections. By including the speed limit as a variable, a prediction model for speed on horizontal curve, as shown in *Table 2.9*, was obtained.

Table 2.9 – Fitzpatrick et al.'s model for horizontal curve sites

Variables	**Parameter Estimate**	***p*-value**	**Variation Inflation Factor**
Intercept	43	0.0001	0.000
Speed limit (km/h)	0.52	0.0001	1.021
Deflection angle (°)	-0.15	0.0183	1.025
Access density*	4.4	0.0262	1.007
R^2 = 75%	*F*-statistic = 15.341		
Adjusted R^2 = 71%	*p*-value = 0.0001		

* If below 12 points/km then 1, otherwise 0

Unfortunately, when speed limit was included for the straight section model, all other variables were found to be insignificant. Thus, omitting the speed limit factor resulted in a significant relationship between speed and lane width, as given in *Table 2.10*.

Table 2.10 – Fitzpatrick et al.'s model for straight section sites

Variables	**Parameter Estimate**	***p*-value**
With Speed Limit		
Intercept	29	0.0002
Speed limit (km/h)	0.70	0.0001
R^2 = 54%	*F*-statistic = 40.503	
Adjusted R^2 = 53%	*p*-value = 0.0001	
Without Speed Limit		
Intercept	19	0.2345
Average lane width (m)	15	0.0012
R^2 = 27%	*F*-statistic = 12.594	
Adjusted R^2 = 25%	*p*-value = 0.0012	

Jorgensen & Polak (1993) aimed to evaluate the effects of the personal characteristics and economic theory of driver behaviour on speed choice in Oslo, Norway. The model variables are explained in *Table 2.11* and the results of the analysis are summarised in *Table 2.12*.

Their model suggests that higher average and free speeds are expected for older, more experienced drivers and those who perceive that savings in travel time are of high importance. Interestingly, male drivers tend to drive faster than females, but are less inclined to commit speeding offences in the presence of speed limit signs. Also, drivers' perceived loss in penalty costs seems to have a higher significance than their perceived likelihood to get caught speeding.

Table 2.11 – Variables considered in Jorgensen & Polak's model

Variable	Description	Comment
S^	Driver's measured average speed	Measured on the basis of recorded travel time over the surveyed section of road
S*	Driver's preferred free speed	Stated preferred speed over the surveyed 90 km/h zone under the same driving conditions at the time of survey but in the absence of speed limits
EXP	Driving experience	Calculated as the product of the number of years the driver has possessed a driving licence and the average annual distance driven over the past 3 years
AGE	Driver's age	Measured in years
SEX	Driver's sex	Dummy variable (male = 1, female = 0)
TTS	Importance of travel time savings on current journey	Measured on a five point semantic scale, then grouped into two categories to give indicator variable (high importance = 1, low importance = 0)
PPC	Perceived likelihood of being caught speeding on the surveyed section of road	Measured on a six point semantic scale then grouped into two categories to give indicator variable (likely = 1, unlikely = 0)
PLC1 PLC2	Perceived loss if caught exceeding the speed limit by 15 km/h	Measured on a five point semantic scale then grouped into three categories to give two indicator variables corresponding to high (PLC1 = PLC2 = 1), moderate (PLC1 = 0, PLC2 = 1) and low (PLC1 = PLC2 = 0) levels of loss

Table 2.12 – Results of Jorgensen & Polak's model

Variable	**Coefficient (and t-statistic)**	
	Without Speed Limit (Dependent variable = S)*	*With Speed Limit (Dependent variable = S^)*
EXP	0.010 (1.7)	0.009 (2.0)
AGE	-0.115 (-7.3)	-0.025 (-1.8)
SEX	0.036 (2.6)	-0.009 (-0.7)
TTS	0.052 (4.6)	0.035 (3.3)
PPC	-	0.0003 (0.3)
PLC1	-	-0.024 (-2.6)
PLC2	-	-0.024 (-1.2)
Diagnostics		
N	508	508
R^2	0.21	0.07
F	33.8	4.8

2.4.2 *Predicting speed on traffic-calmed streets*

For the most part, speed modelling has been centred on roads that cater for high-speed and high-volume traffic. There is limited amount of work done for the prediction of speeds on low volume roads, i.e. local streets. This is probably due to these streets requiring minimal design standards.

Speed modelling on local streets is predominantly carried out to gauge the performance of traffic calming measures and provide guidance for design. Taylor (1986) proposed a "control theory" approach to modelling speeds on streets restrained by speed control devices that enabled the estimation of optimum spacing and location of control measures to meet the planner's target speed for the street.

Brindle and Lydon (1998) produced speed models for estimating mean speeds between two angled slow points and two flat-top speed humps (see *Figure 2.7*). The models showed that the mean operating speeds for both devices were about 30% lower than the mean speeds 60 m before the devices. Mean speeds recovered to the same level 50 m after the speed hump and 70 m after the angled slow point.

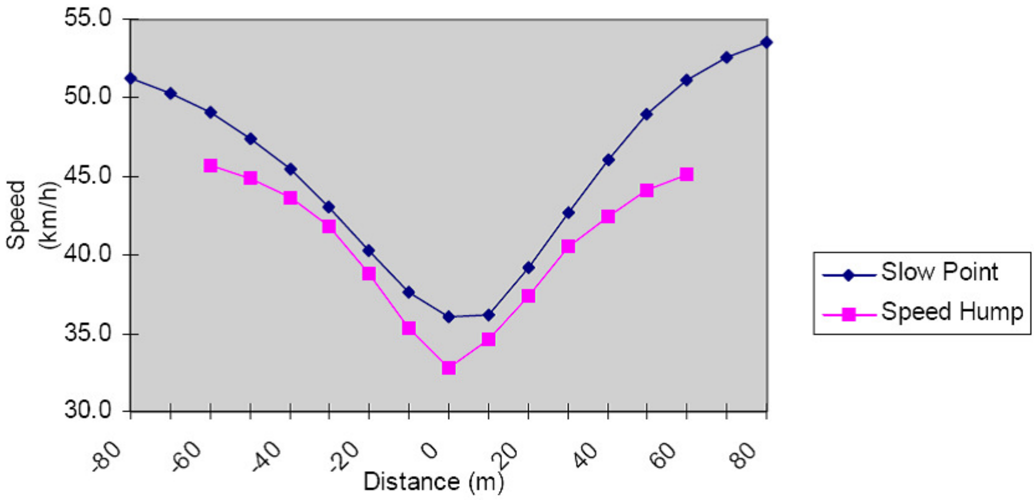


Figure 2.7 – Consolidated mean speed profiles for angled slow point and speed hump (source: Brindle and Lydon, 1998)

Speed-based design models provide a way of obtaining estimates for speed and zone of influence on a section of road restrained by traffic calming devices. This is performed by superimposing the generalised speed profile (from a speed model) onto the existing speed profile (before treatment). *Figure 2.8* provides an illustration of this method.

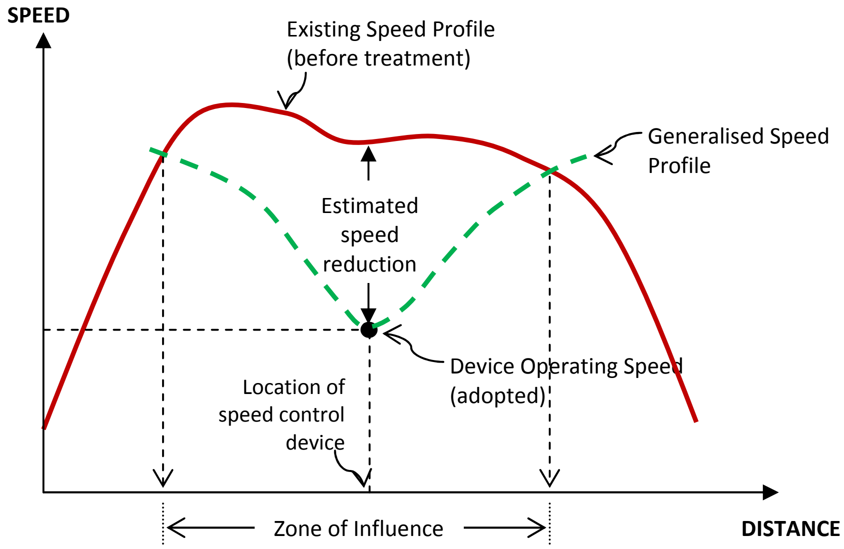


Figure 2.8 – Method of obtaining estimates for speed and zone of influence for a planned speed control device

Webster (1993) attempted to associate speeds midway between speed control devices with spacing between devices through linear relationships and obtained the following models:

For speed midway between 100 mm high round-top road humps,

$$V_1 = 16.73 + 0.087 * S \quad (r = 0.80, S.E. = 1.59) \tag{2.3}$$

$$V_2 = 12.10 + 0.092 * S \quad (r = 0.87, S.E. = 1.28) \tag{2.4}$$

For speed midway between 100 mm high flat-top road humps with an average slope of 1:10,

$$V_1 = 12.95 + 0.107 * S \quad (r = 0.93, S.E. = 1.70) \tag{2.5}$$

$$V_2 = 11.06 + 0.090 * S \quad (r = 0.91, S.E. = 1.61) \tag{2.6}$$

where V_1 = 85^{th} percentile speed (mph)
V_2 = mean speed (mph)
S = hump separation (m)
r = correlation coefficient
$S.E.$ = standard error (mph)

Webster's models indicate that speeds between road humps generally increase with spacing, and that speeds between flat-top humps are higher compared to round-top humps. However, at larger spacings, speeds may be exaggerated due to the nature of linear functions that imply speeds increase indefinitely with spacing.

Barbosa et al. (2000) studied four types of traffic calming devices used in sequence in York, England and obtained a linear regression model that enables the estimation of speed profiles along streets with speed humps, speed tables, speed cushions and chicanes.

Table 2.13 describes the variables and parameter estimates in Barbosa et al.'s model, which was found to have an R-squared value of 0.55. The significance values of the model and parameter estimates were, however, not reported.

According to the model, speed tables have the ability to produce the largest speed reduction of 7 km/h, followed by speed humps (4.5 km/h), chicanes (2 km/h) and speed cushions (1 km/h).

Table 2.13 – Barbosa et al.'s speed profile model

Variables	Description	Parameter Estimate
Intercept		-8.73
V_1	Entry speed, i.e. the initial speed in the link which was assumed as the speed measured at the first sensor during data collection (in km/h)	0.62
dt	Distance to the next device in the direction of travel (in m)	0.23
df	Distance from the previous device in the direction of travel (in m)	0.78
dt^2	The second order of *dt*	-0.0012
df^2	The second order of *df*	-0.0137
df^3	The third order of *df*	0.05
H	Speed hump; dummy variable used to indicate presence a hump (0 or 1)	-4.48
T	Speed table; dummy variable used to indicate presence a table (0 or 1)	-6.71
C	Speed cushion; dummy variable used to indicate presence a cushion (0 or 1)	-0.86
Ch	Chicane; dummy variable used to indicate presence a chicane (0 or 1)	-2.01

2.5 Estimating road traffic noise

Road traffic is the most common source of noise and a prevalent cause of annoyance. Noise annoyance is a feeling of displeasure induced by exposure to noise, which may cause psychological and health problems when regularly exposed (Berglund et al., 1999; WHO, 2011).

A study in the UK showed that just 10% of people were annoyed when road traffic noise exposure level, taken as the continuous equivalent A-weighted sound level over an 18-hour period ($L_{Aeq,18h}$), was 55 dB. As the exposure levels increased, people became more annoyed, with 50% and 75% reporting that they were annoyed when the exposure levels were 66 dB and in excess of 81 dB respectively (Highways Agency, 2011).

The overall noise produced by a vehicle comes from a number of sources that can be classified into three key categories: mechanical noise, rolling noise, and aerodynamic noise. Mechanical noise is generally engine, exhaust, and induction noise. It may also include body rattling of the vehicle, and engine braking by heavy vehicles. Rolling noise is the result of tyre-road interaction, while aerodynamic noise originates from rapid movement of a vehicle through the air (NZS 6801:2008).

At lower speeds (< 50 km/h), the predominant sources of noise are the vehicle engine and drivetrain. At higher speeds (> 50 km/h), tyre-road and aerodynamic noise become more dominant (Homburger et al., 2001).

The prediction of road traffic noise (RTN) is useful for the assessment of environmental noise impact for new and existing roads or road improvements, and for the evaluation of noise mitigation measures. This allows local authorities to maintain environmental standards that preserve the quality of life, particularly for communities living close to road transport facilities.

Noise annoyance is widespread in communities affected by their proximity to state highways and arterials. This is due to high levels of traffic volume and speed, and high percentages of heavy vehicles, the three important variables that influence RTN (FHWA, 1980). Other variables often considered in RTN models include distance between source and receiver, and road surface type. Corrective factors are normally introduced in RTN models to account for the effects of ground condition, atmospheric absorption, reflection, diffraction, and meteorology on sound propagation. The following section presents examples of RTN models.

2.5.1 Road traffic noise models

Some of the earliest RTN models were aimed at predicting the noise level exceeded for 50% of the measurement duration (L_{50}) using traffic volume (Q) and distance between source and receiver (d) as contributory variables. As time progressed, other variables of great importance such as speed (v) and percentage of heavy vehicles (P) were included. *Table 2.14* shows the advancement of the L_{50} prediction models.

Table 2.14 – L_{50} prediction models

Model	Source
$L_{50} = 68 + 8.5\log_{10}(Q) - 20\log_{10}(d)$	Bolt et al. (1952)
$L_{50} = 3.5 + 10\log_{10}\left(\frac{Qv^3}{d}\right)$	Johnson & Saunders (1968)
$L_{50} = 20 + 10\log_{10}\left(\frac{Qv^2}{d}\right) + 0.4P$	Galloway, Clark & Kerrick (1969)

In the following years, the equivalent sound level (L_{eq}) was extensively used as a sound level indicator. *Table 2.15* provides examples of RTN models that predict L_{eq}. Note that some of these models attempt to relate percentile sound indicators (L_{10}, L_{50}, L_{90}) to L_{eq}.

Table 2.15 – L_{eq} prediction models

Model	Source
$L_{eq} = L_{50} + 0.018(L_{10} - L_{90})^2$ where $L_{10} = 61 + 8.4\log_{10}(Q) + 0.15P - 11.5\log_{10}(d)$ $L_{50} = 44.8 + 10.8\log_{10}(Q) + 0.12P - 9.6\log_{10}(d)$ $L_{90} = 39.1 + 10.5\log_{10}(Q) + 0.06P - 9.3\log_{10}(d)$	Griffiths & Langdon (1968)
$L_{eq} = 38.8 + 15\log_{10}(Q) - 10\log_{10}(W)$ where W is the road width (m)	Josse (1972)
$L_{eq} = 55.5 + 10.2\log_{10}(Q) + 0.3P - 19.3\log_{10}\left(\frac{W}{2}\right)$	Burgess (1977)
$L_{eq} = 0.65L_{50} + 28.8$ where, for urban roads and highways with Q < 1000 veh/hr: $L_{50} = 11.9\log_{10}(Q) + 31.4$ for urban roads with elevated buildings near the carriageway edge and road with L (in metres): $L_{50} = 15.5\log_{10}(Q) - 10\log_{10}(L) + 36$	CSTB (1991)
$L_{eq} = 10\log_{10}(Q_L + Q_M + 8Q_H + 88Q_B) + 33.5$ where Q_L, Q_M, Q_H and Q_B is the flow (veh/h) for light vehicles, motorcycles, heavy vehicles and buses respectively	Fagotti & Poggi (1995)

The Calculation of Road Traffic Noise (CRTN) is one of the most recognised procedures for predicting traffic noise. Developed in the UK in 1975 and later revised in 1988 by the Transport and Road Research Laboratory and the Department for Transport, the CRTN procedure contains models for the estimation of the hourly L_{10} or the 18-hour L_{10}, as given below:

$$L_{10,1h} = 42.2 + 10\log_{10}(q) \tag{2.7}$$

$$L_{10,18h} = 29.1 + 10\log_{10}(Q) \tag{2.8}$$

where q and Q are the hourly traffic flow (veh/hour) and 18-hour flow (veh/hour) respectively. The basic models are for a traffic stream with no heavy vehicles in it, travelling on a flat road and having a mean speed of 75 km/h.

The noise levels will require correction, taking into account actual mean speed, composition of heavy vehicles, road gradient and road surface type. Further correction is necessary for the effects of distance, ground cover, obstruction, reflection and angle of view (Department of Transport, 1988).

The German RTN model, RLS-90 (*Richtlinien für den Lärmschutz an Straßen*, or Guidelines for the Protection against Noise in the Streets) is another relevant model which requires input such as average hourly flow for motorcycles, heavy and light vehicles, mean speed for each vehicle group, and the dimension, geometry and type of road and obstructions. Corrections for speed limit, road surface type and rise and falls along roads are taken into account, while corrections for the effects of air absorption, reflection and diffraction on sound propagation are also considered in the model.

The basic model in RLS-90 is used for the prediction of the average sound level for a single lane, measured 25 m from the centre of the lane ($L_{m,E}^{(25)}$). It takes the following form:

$$L_{m,E}^{(25)} = 37.3 + 10\log_{10}[Q(1 + 0.082P)] \qquad (2.9)$$

where Q is the traffic flow in vehicles/hour and P is the percentage of heavy trucks weighing more than 2.8 tons. The model assumes an ideal condition where speed is 100 km/h and road gradient is less than 5%. When settings deviate from the ideal conditions, the aforementioned corrections are applied to equation 2.8 (RLS, 1990; cited in Quartieri et al., 2009).

The Acoustical Society of Japan (ASJ) also prescribes an applicable RTN model which predicts the L_{Aeq} for distances up to 200 m from the road and heights up to 12 m above ground. The procedure begins with determining the sound power level of a running vehicle (L_{WA}) using the following model:

$$L_{WA} = a + b\log_{10}(V) + C \tag{2.10}$$

where V is the vehicle speed (km/h), a and b are coefficients based on vehicle category and flow condition, and C is the correction term for road gradient, sound radiation directivity, and noise reduction due to road surface.

The next step is obtaining the sound pressure level (L_A) using the following model:

$$L_{A,i} = L_{WA,i} - 8 - 20\log_{10}(r_i) + \Delta L_{cor,i} \tag{2.11}$$

where $L_{WA,i}$ is the sound power level of a single running vehicle at the i-th section, r_i is the direct distance from the source to the prediction point (m), and $\Delta L_{cor,i}$ is the correction related to attenuation factors such as diffraction, ground and atmospheric absorption.

The third step is the calculation of the sound exposure level (L_{AE}) using the following equation:

$$L_{AE} = 10\log_{10}\left(\frac{1}{T_o}\sum_i 10^{\frac{L_{A,i}}{10}} * \Delta t_i\right) \tag{2.12}$$

where T_o is the reference time of sound exposure, typically 1 s, and Δt_i is the time when the sound source exists in the i-th section (s).

The final step is the calculation of the continuous equivalent sound pressure level (L_{Aeq}) using the following equation:

$$L_{Aeq,T} = L_{AE} + 10\log_{10}\left(\frac{N_T}{T}\right) \tag{2.13}$$

where N_T is the number of vehicles and T is the time interval (s).

The procedure summarised above is to determine the L_{Aeq} for a vehicle category per lane. Hence, the L_{Aeq} for all vehicle categories and all lanes are determined through a similar process (Yamamoto, 2010).

2.5.2 *Predicting traffic noise on traffic-calmed streets*

RTN models are primarily used for the evaluation of traffic noise on roads that serve high traffic volumes and speeds. Some models offer adjustment for low volumes and interrupted flows (e.g. traffic at signalised intersections). However, applying these RTN models to local streets may not result in predicted sound levels that are representative of the traffic on local streets, mainly due to the nature of the flow.

In the past, there have been RTN models specifically developed for interrupted flows (Kokowski & Makarewicz, 1997; Pamanikabud & Tharasawatpipat, 1999) which may serve as guidance for the development of models for traffic-calmed streets, given that the movement of vehicles also involves acceleration and deceleration at portions of the street.

Traffic on local streets is very low compared to arterials and state highways, and is composed of a tiny percentage of heavy vehicles. FHWA (1980) suggests that the sound of traffic on a road carrying 2,000 vehicles per hour is twice the sound when flow is 200 vehicles per hour.

Therefore, noise standards advise against the use of RTN models for roads having low daily traffic, and generally, applying the noise standards itself. The New Zealand NZS6806 standard, for example, states that roads predicted to carry annual average daily traffic (AADT) less than 2,000 vehicles per day shall be excluded.

In general, noise annoyance due to traffic is not prevalent on local streets. Complaints about traffic noise in neighbourhoods are random and often deal with excessive speeding and noise generated when vehicles run over vertical speed control devices.

While there have been many before-and-after studies done to evaluate the noise impact of vertical deflections, few studies have been carried out to predict noise levels across these devices.

Abbott et al. (1995) produced a set of logarithmic regression models for the prediction of maximum noise levels (L_{Amax}) emitted by various light and heavy vehicles across speed cushions and speed humps, using speed as the influencing factor. The basic model has the following form:

$$L_{A\max} = A + B\log_{10}(V) \tag{2.14}$$

where V is the vehicle speed (km/h), A is the constant and B is the coefficient of the base 10 logarithm of speed parameter. *Table 2.16* summarises the models obtained for passenger cars.

Table 2.16 – Abbott et al.'s regression analysis of vehicle noise and speed for passenger cars

Device	*A*	*B*	*r*	*SD*
Narrow Cushion				
75 mm x 2000 mm x 1600 mm, Asphalt	19.7	30.4	0.98	1.1
65 mm x 3500 mm x 1600 mm, Asphalt	29.7	23.2	0.98	0.8
60 mm x 3500 mm x 1500 mm, Asphalt	15.8	33.1	0.99	0.7
Average	21.8	28.9	0.97	1.1
Wide Cushion				
75 mm x 2000 mm x 1900 mm, Asphalt	27.3	25.6	0.98	1.0
65 mm x 2000 mm x 1900 mm, Asphalt, 2 cushions in single file 4 m apart	6.8	41.2	0.95	2.2
75 mm x 1950 mm x 1900 mm, Moulded Rubber	20.2	31.8	0.99	0.9
80 mm x 2380 mm x 1880 mm, Moulded Rubber	25.8	27.1	0.99	0.6
Average	20.2	31.3	0.94	1.7
Humps				
Flat-top, 75 mm x 7800 mm x 4000 mm, Asphalt	14.4	34.5	0.94	2.1
Round-top, 75 mm x 3700 mm x 4000 mm, Asphalt	23.8	27.6	0.96	1.4
Average	18.5	31.5	0.94	1.8
Level *(control)*				
Fine textured asphalt	17.2	33.8	0.99	0.6

A and *B* is the constant and coefficient, respectively, for equation 2.12
r is the correlation coefficient
SD is the standard deviation, in dB(A)

While Abbott et al.'s research provides some guidance for the selection of devices based on noise impact at conventional speeds (15 – 40 km/h); the logarithmic models may not be valid for very low speeds, where the corresponding predicted noise levels become negative. The use of a single test vehicle (Ford Escort 1.6 litre petrol engine saloon) running at various speeds to represent the passenger car category may not actually exemplify that category well, given the different types of passenger cars that are currently available.

2.6 Implications of literature review for this research

The main goal of this research is to study the impact of speed control devices on drivers' speed choice, safety and the environment in residential settings. The review of literature relating to neighbourhood traffic management was performed in order to provide motivation for this research, to map out ways of improving existing research methods and analyses, and to find knowledge gaps that could potentially be filled by the findings from this research.

The limited amount of research and published findings on the impact of traffic calming in New Zealand was the main incentive for conducting this research. Despite having a wide range of traffic calming measures being applied to residential streets around New Zealand, there has been little effort made to evaluate these measures.

The speed-based design models for the selection and placement of traffic calming devices are straightforward yet reliable tools that could be expanded in terms of having generalised speed profiles for an array of devices. This research not only attempts to produce such speed profiles, but at the same time attempts to provide designs better suited for the New Zealand scene, and which of course can be adapted by other countries as well.

For multiple speed control devices used in sequence, the spacing of devices is crucial, which is why studies have been conducted in the past to provide guidelines for device spacing. Webster's speed-spacing models, for instance, uses linear modelling which tends to overestimate inter-device speeds at large spacings. This research attempts to develop more realistic models which consider the speeds at large spacings, and the speeds that are equivalent to device operating speeds when spacing is effectively zero.

This research also aims to emphasise the variability of speeds at device locations, which has been overlooked in past research, as an important indicator in the assessment of the performance of traffic calming devices. Small variations in (low) device operating speeds are optimal, because it means that most drivers reduce their speeds in order to negotiate devices at low speeds.

The lack of models for estimating noise levels emitted by vehicles traversing vertical speed control devices and disagreement with the model form in Abbott et al.'s study are stimuli for the development of practical traffic noise models, which allow for the estimation of noise levels even at low speeds.

3 Research Methods

This research was split into three stages – speed studies, safety studies and noise studies. The detailing of the selection of study sites, experimental setups and methods used for the collection of data, and the description of analyses performed on the data, are provided in the following sections.

3.1 Site selection, experimental setup and data collection for speed studies

A total of 21 residential streets in Christchurch (New Zealand) were selected for the speed studies. Traffic calming measures were already implemented on these streets mainly through the use of speed humps, speed tables, angled slow points and narrowings.

These streets are classified as low volume roads, which are roads that carry an average daily traffic flow of less than 500 vehicles (Christchurch City Council, 2009).

Seven streets had single devices, while the other 14 had multiple devices. All sites were through streets with provision for kerbside parking either on the carriageway or indented bays. A general description of each street and its device(s) is given in *Tables 3.1* and *3.2*. For photographs, refer to *Appendix A*.

In addition, three long streets (lengths greater than 400 m) without mid-block speed restraint measures were included to represent the effect of large spacings between vertical speed control devices on speed. The intersections at both ends of these streets effectively function as speed regulators. The long streets chosen were Longmuir Street, Ilam (430 m long, 9.2 m wide), Dalkeith Street, Hoon Hay (440 m, 9.4 m) and Oakhampton Street, Hornby (680 m, 9.3 m).

Table 3.1 – Overview of streets selected for speed studies on single devices

Street Name, Suburb	Street Width (m)	Device	Device Dimensions
Burke Street, Addington	12.5	Speed hump	Watts profile 100 mm (H) x 3.7 m (L) x 5.8 m (W)
Randolph Street, Woolston	9.0	Speed table	120 mm (H) x 5.8 m (L) x 8.3 m (W) 1:8 ramp gradient
Mackenzie Avenue, Woolston	8.7	Angled slow point One-lane, flush	5.1 (L) x 3.0 (W)
Rattray Street, Riccarton	8.3	Angled slow point One-lane, raised	50 mm (H) x 16.0 m (L) x 3.2 m (W) 1:20 ramp gradient
Stratford Street, Fendalton	10.0	Narrowing One-lane, flush (asphalt)	11.6 m (L) x 3.6 m (W)
Kirkwood Avenue, Ilam	9.5	Narrowing One-lane, raised	50 mm (H) x 3.0 m (L) x 4.6 m (W) 1:40 ramp gradient
Hamilton Avenue, Ilam	9.0	Narrowing Two-lane, flush (textured)	6.0 m (L) x 3.6 m (W)

H, L and W denote constructed height, length and width respectively.
All streets provide for carriageway parking on both sides.

Table 3.2 – Overview of streets selected for speed studies on multiple devices

Street Name, Suburb	Street Width (m)	Device and Number of devices studied	Device Dimensions
Snowdon Road, Fendalton	9.7	Speed hump, 4	Watts profile 100 mm (H) x 3.7 (L) x 5.6 (W)
St Asaph Street, Phillipstown	11.8	Speed hump, 2	Watts profile 100 mm (H) x 3.8 (L) x 6.5 (W)
Quinns Road[a], Shirley	8.5	Speed hump, 2	Watts profile 100 mm (H) x 3.8 (L) x 7.8 (W)
Brockworth Place, Riccarton	13.5	Speed hump, 2	Watts profile 100 mm (H) x 3.8 (L) x 6.0 (W)
Reynolds Avenue, Bishopdale	10.0	Speed hump, 2	Watts profile 100 mm (H) x 3.8 (L) x 9.0 (W)
Wattle Drive, New Brighton	8.1	Speed hump, 2	Watts profile 100 mm (H) x 3.6 (L) x 7.3 (W)
King Street, Sydenham	13.2	Speed hump, 2	Watts profile 100 mm (H) x 3.7 (L) x 9.0 (W)

Devon Street, Addington	9.7	Speed hump, 2	Watts profile 100 mm (H) x 3.8 (L) x 8.7 (W)
Tankerville Street, Hoon Hay	11.4	Speed hump, 3	Watts profile 100 mm (H) x 3.8 (L) x 10.4 (W)
Aylesford Street, Mairehau	10.6	Speed table, 6	75 mm (H) x 5.0 (L) x 5.5 (W) 1:12 ramp gradient
Francis Avenue, Mairehau	8.2	Speed table, 3	75 mm (H) x 5.0 (L) x 4.5 (W) 1:12 Ramp gradient
Studholme Street[b], Somerfield	8.3	Speed table, 2	75 mm (H) x 4.9 (L) x 6.4 (W) 1:12 ramp gradient
Garden Road, Fendalton	9.7	Speed table, 2	75 mm (H) x 3.6 (L) x 5.4 (W) 1:26 ramp gradient
Joy Street, Shirley	10.7	Speed table, 2	75 mm (H) x 3.7 (L) x 6.2 (W) 1:10 ramp gradient

H, L and W denote constructed height, length and width respectively.
All streets provide for carriageway parking on both sides, except for the following:
a: Parking allowed on one side only along the study section.
b: Indented parking.

Speed data were collected using a ProLaser III light detection and ranging (LIDAR) speed gun. The reason for choosing a manual collection method was principally to acquire longitudinal speed profiles of individual vehicles. This would enable the investigation of variations between drivers in terms of speed choice and their response to the devices.

Data were collected during weekday off-peak periods for the purpose of obtaining vehicular speeds unimpeded by other traffic. Sample sizes ranged between 100 and 350 vehicles per site. Naturally, larger samples were obtained for higher trafficked streets.

To minimise the effect of parked vehicles, streets with effective widths wide enough to allow opposing vehicles to pass each other without the need to slow down or stop were selected. Given that parking density was very low during off-peak periods, the effect of parked vehicles was negligible.

Data were collected in clear and dry conditions for the intention of eliminating factors that affect driving, such as lack of visibility and wet road surfaces.

To rule out the effect an observer might have on drivers' speed choice, observations were made from a vehicle parked by the side of the road, with the observer concealed from the view of drivers. The position of the vehicle was also chosen so as not to impede traffic. *Figure 3.1* shows the layout for speed data collection.

To ensure that the recordings of the speed gun were reliable, the instrument was calibrated by testing its range (distance in meter) readings with actual measurements using a measuring wheel. A test car, in which the driver was instructed to travel at constant speeds of about 30 km/h, 40 km/h and 50 km/h, was also used to test for reliability and obtain appropriate distances (angles) for speed measurement. It was found that target vehicles needed to be no less than 30 m from the observer in order to obtain reliable readings.

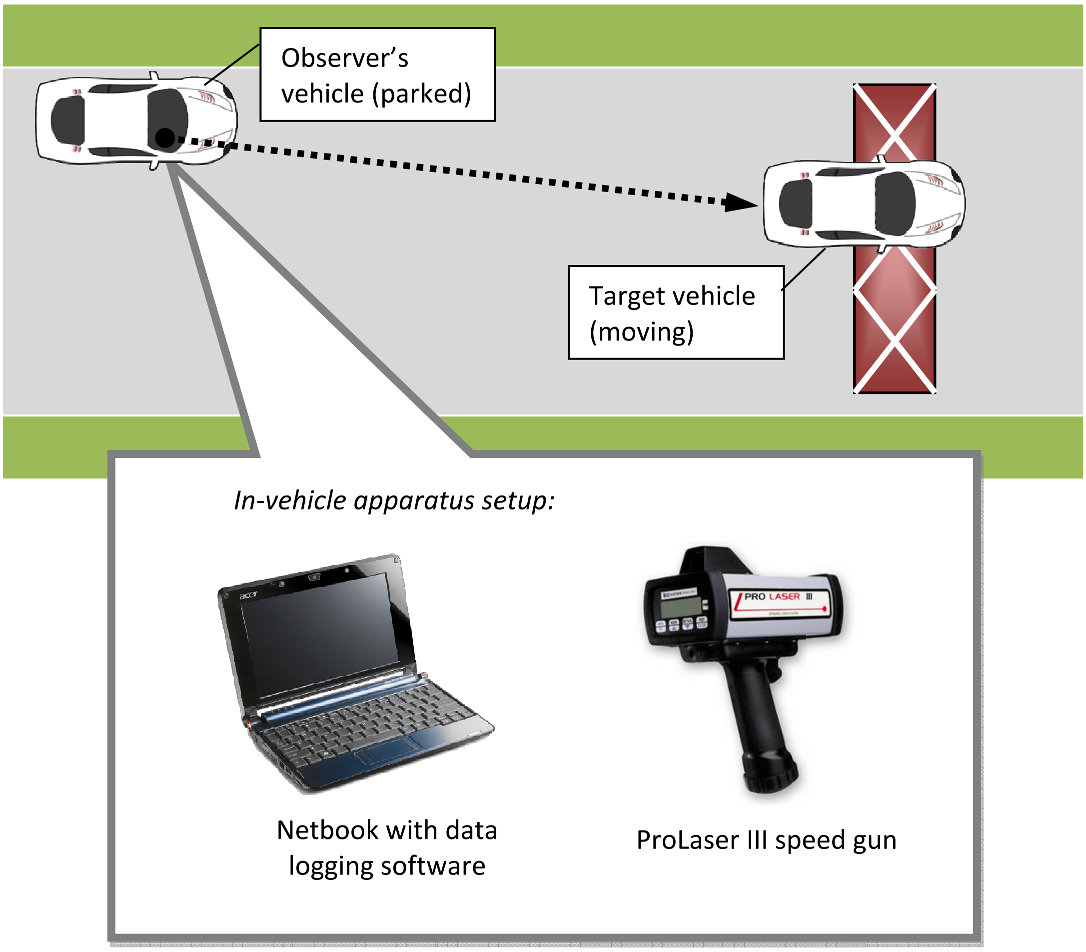


Figure 3.1 – Experimental setup for speed data collection

There were some limitations with using the speed gun. Difficulty in obtaining the speed of a target vehicle was experienced in the following conditions:

- When the target vehicle was moving at distances greater than 500 m from the observation point. The speed gun did not perform up to expectations at large distances, although the technical specifications claim the ability to detect at distances up to 1,330 m.
- During extremely hot and sunny weather with low humidity. This is explained by over-exposure error cause by sun flare reflected off the target vehicle, and/or sweep error due to the formation of a visible mirage of the target vehicle. Such errors were found to mostly occur at greater distances from the observer.

These limitations, however, did not affect the results of the speed studies because it was obvious from the data when the above-mentioned problems had occurred, and the data for affected vehicles were not included in the analysis. The only shortcoming was the number of missed opportunities of obtaining complete speed profiles at longer distances along the streets.

3.2 Speed profiling

The empirical speed-based design process developed by Brindle (2005) and the field trial method conducted by Jurewicz (2009) were used as the basis for the study of speed profiles.

The first step in the speed profiling process was the extraction of speed and distance data from the logs, which were in CSV (comma-separated values) format. This was done using Microsoft Excel. Since the main outputs from the LIDAR device are range and time, speed had to be calculated using consecutive range-time values.

The second step was the grouping of speed data into uniformly-sized distance classes (10 m intervals) covering most of the street length. The interval for a traffic calming device, however, differed as it was represented by the longitudinal length of the device.

The final step involved the calculation of 85th percentile speeds, mean speeds and standard deviation for each interval, and the plotting of speed profiles. Consequently, three speed profiles were obtained for each street – 85th percentile speed profile, mean speed profile and standard deviation profile (see *Figure 3.2*).

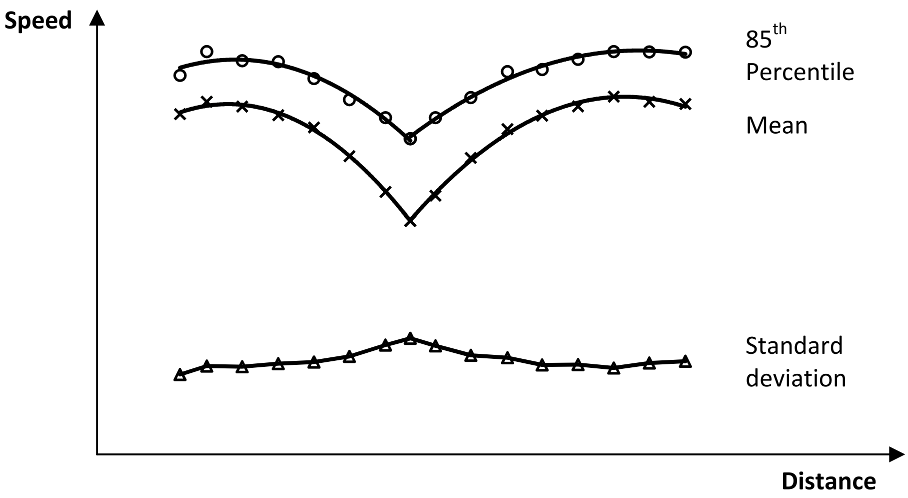


Figure 3.2 – Example of speed profiles produced for each street

The 85th percentile speed and mean speed profiles were used to determine the speed-reducing effect and zone of influence for each type of traffic calming device.

The speed-reducing effect is the drop in speed as a result of traffic calming measures. This effect is represented by the speed change, i.e. street speed minus device operating speed.

Street speed was taken as the 85th percentile speed recorded on unimpeded sections (where speeds were observed to be the highest), while the device operating speed was ideally the 85th percentile speed recorded across the traffic calming device. The zone of influence is the area over which a device produces a noticeable speed-reducing effect.

The standard deviation profiles were used to examine the variation in speeds at the devices and on unimpeded sections of the street.

A typical speed profile showing the 85th percentile speeds at varying distances along a traffic-calmed street is shown in *Figure 3.3*, along with some of the terminology used.

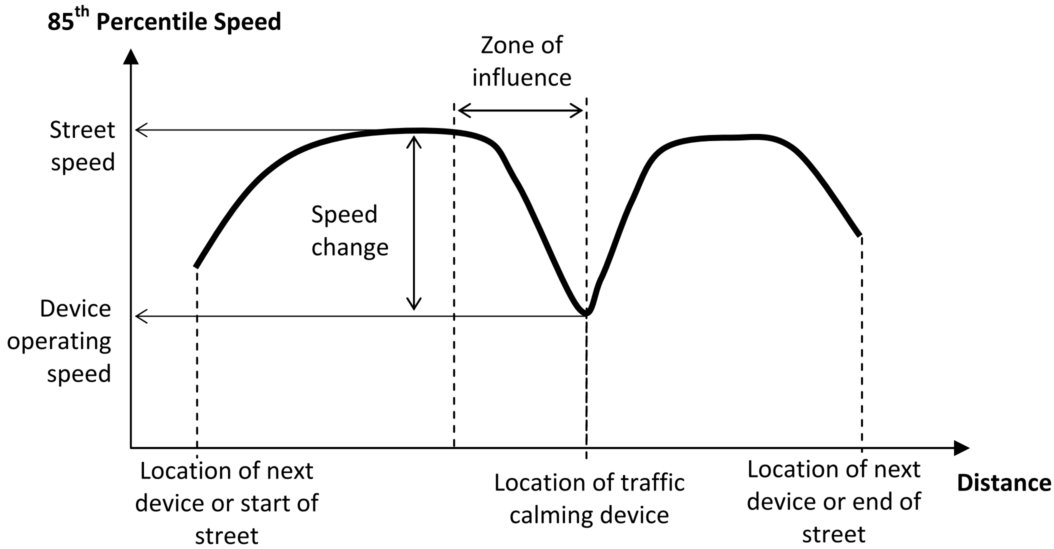


Figure 3.3 – A typical speed profile and some terminology used

3.3 Testing for variation in speeds

Deviations from the mean speed may arise from the implementation of traffic calming measures, as drivers' choice of speed is fairly inconsistent across calming devices. A plot of standard deviations at distances along a calmed-street, shown previously in *Figure 3.2*, gives a general idea of these differences.

Three tests for equality of variances – *F*-test, Bartlett's test and Levene's test – were employed to assess the statistical significance of the variation in speeds across impeded segments (i.e. at the device) and unimpeded segments (i.e. at distances from the device).

These tests were performed on streets with single devices. *Figure 3.4* illustrates the segments on a traffic-calmed street that were tested. The variation in speed at the impeded segment was compared with the variations in speed at 10 m intervals moving towards (+) and away from (–) the device.

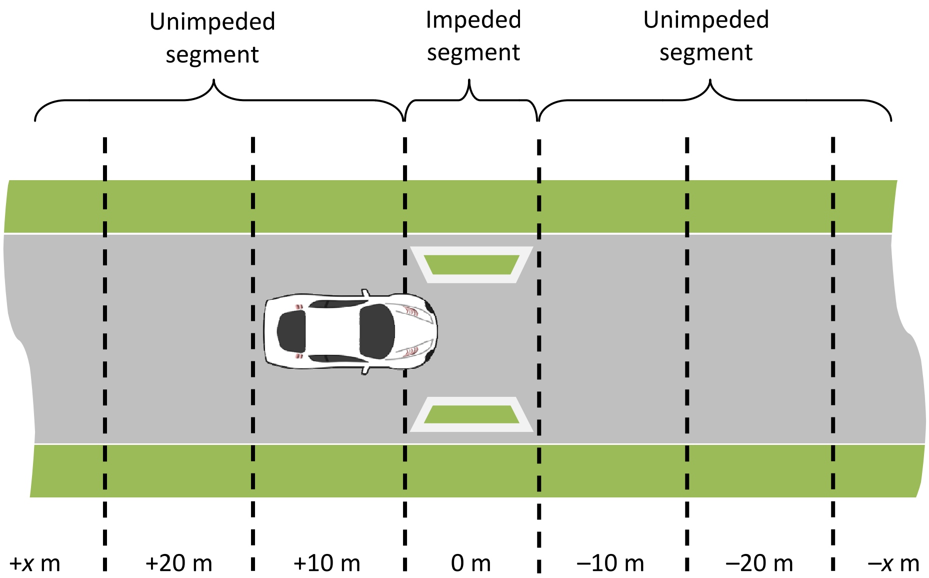


Figure 3.4 – Segments tested in the study of variation in speeds

3.3.1 Testing for Normality

Since the data were assumed to be Normally distributed, tests for Normality were carried out in preparation for the test for equality of variances. The tests were performed at three locations on each street, i.e. at the device and at two mid-point locations on the unimpeded segments. Two test statistics were chosen; the Kolmogorov-Smirnov (K-S) test and the Anderson-Darling (A-D) test. These tests were performed using @RISK software, which had the ability to fit distributions.

The K-S statistic is defined as:

$$D_n = \sup \left| F_n(x) - \hat{F}(x) \right| \tag{3.1}$$

where *sup* is the supremum or greatest value, n is the total number of data points, $\hat{F}(x)$ is the fitted cumulative distribution function (CDF) and $F_n(x) = N_x/N$, where N_x is the number of X's less than x.

The K-S test is more focused on the centre of the distribution, thus does not detect tail discrepancies very well. This was resolved by the A-D test, which highlights differences between the tails of the fitted distribution and input data.

The A-D statistic is defined as:

$$A^2{}_n = n \int_{-\infty}^{+\infty} \left(F_n(x) - \hat{F}(x) \right)^2 \Psi(x) \hat{f}(x) dx \tag{3.2}$$

where n is the total number of data points, $\hat{f}(x)$ is the hypothesised density function, $\hat{F}(x)$ is the hypothesised CDF, $F_n(x) = N_x/N$, where N_x is the number of X's less than x and $\Psi(x)$ is given by the formula:

$$\Psi(x) = \frac{1}{\hat{F}(x)\left[1 - \hat{F}(x)\right]} \tag{3.3}$$

These statistics measure how well a Normal distribution fits the input data; the smaller the value, the better the fit (Palisade, 2010).

For both Normality tests, the null hypothesis (H_o) states that the data follows a Normal distribution, while the alternative hypothesis (H_a) states that data does not follow a Normal distribution. The null hypothesis is rejected when the test statistic is larger than the critical value at a significance level (α) of 0.05.

The K-S and A-D Normality tests are stringent in the sense that even a small deviation from Normality is considered a significant difference. Therefore, these tests were not exclusively used for checking Normality.

In addition to obtaining K-S and A-D statistic values for each data set, a frequency histogram with Normal overlay and a Normal Q-Q plot (a plot of expected and observed quantiles) were produced in order to perform a visual inspection of the goodness of fit to a Normal distribution.

A bell-shaped frequency histogram (see *Figure 3.5*) and a Q-Q plot that closely follows the $y = x$ line (see *Figure 3.6*) indicate that the data is approximately Normally distributed.

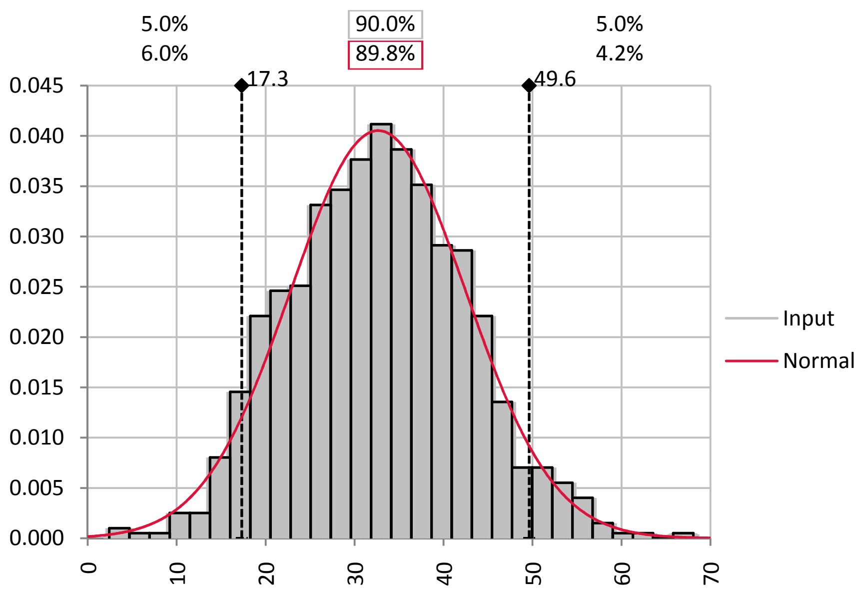


Figure 3.5 – Frequency histogram showing an approximately Normal distribution

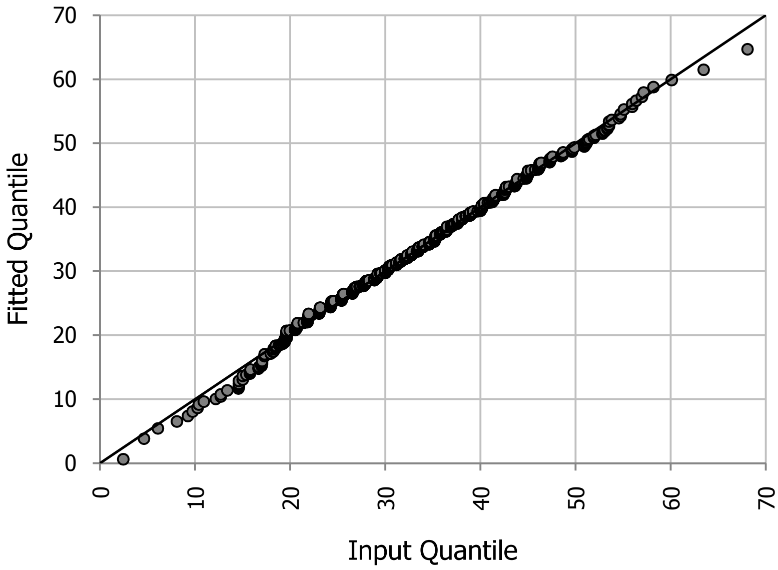


Figure 3.6 – Normal Q-Q plot suggesting that the data is approximately Normally distributed

Based on the e-Handbook on Engineering Statistics (NIST/Semantech, 2003-2012), methods for the equality of variances tests are explained in the following sub-sections.

3.3.2 F-test for equality of two variances

The *F*-test, which assumes that the speeds are Normally distributed, was used to test the null hypothesis that the standard deviations of two populations are equal. This test can be either a two-tailed or one-tailed test. For this study, the one-tailed version was used to test against the alternative hypothesis that the standard deviation of the first population is either greater than or less than the standard deviation of the second population.

The null and alternative hypotheses are defined as:

H_o: $\sigma_1 = \sigma_2$

H_a: $\sigma_1 < \sigma_2$ for a lower one-tailed test

$\sigma_1 > \sigma_2$ for an upper one-tailed test

where σ_1 and σ_2 are the standard deviations for the first and second population, respectively.

The *F*-test statistic is given by the formula:

$$F = \frac{s^2{}_1}{s^2{}_2} \tag{3.4}$$

where $s^2{}_1$ and $s^2{}_2$ are the variances for the first and second population, respectively.

The null hypothesis is rejected (i.e. the two standard deviations are not equal) if:

$F < F_{(1-\alpha,\, N1-1,\, N2-1)}$ for a lower one-tailed test

$F > F_{(\alpha,\, N1-1,\, N2-1)}$ for an upper one-tailed test

where $F_{(\alpha,\, df1,\, df2)}$ is the critical value of the *F* distribution with *df*1 and *df*2 degrees of freedom at a significance level of α. *N*1 is the size of the first population and *N*2 is the size of the second population.

3.3.3 Bartlett's test for equality of variances

Bartlett's test was used to test the null hypothesis that *k* samples have equal variances. The alternative hypothesis states that at least one of the variances was different.

Bartlett's test is based on the assumption that the speeds are Normally distributed. Therefore, it is sensitive to departures from Normality. Bartlett's test is one-tailed test that uses a chi-square statistic.

The null and alternative hypotheses are defined as:

H_o: $\sigma_1 = \sigma_2 = \ldots = \sigma_k$

H_a: $\sigma_i \neq \sigma_j$ for at least one pair (i,j)

Bartlett's test statistic, T is determined using this formula:

$$T = \frac{(N-k)\ln s^2{}_p - \sum_{i=1}^{k}(N_i - 1)\ln s^2{}_i}{1 + \left(\frac{1}{3(k-1)}\right)\left[\left(\sum_{i=1}^{k}\frac{1}{N_i - 1}\right) - \left(\frac{1}{N-k}\right)\right]} \tag{3.5}$$

where N is the total sample size, k is the number of groups, N_i is the sample size of the i-th group, $s^2{}_i$ is the variance of the i-th group, and $s^2{}_p$ is the pooled variance, which is given by the formula:

$$s^2{}_p = \frac{\sum_{i=1}^{k}(N_i - 1)s^2{}_i}{N-k} \tag{3.6}$$

The null hypothesis is rejected if:

$$T > \chi^2{}_{(\alpha,k-1)}$$

where $\chi^2{}_{(\alpha,k-1)}$ is the upper critical value of the chi-square distribution with k–1 degrees of freedom and a significance level of α.

3.3.4 Levene's test for equality of variances

Levene's test was used because of its robustness, i.e. the ability to not falsely detect unequal variances when the underlying data are not Normally distributed and the variables are in fact equal.

As with Bartlett's test, the null hypothesis is that the variances of all groups are equal and the alternative hypothesis is that at least one of the variances is different. Levene's Test is one-tailed and uses an F statistic.

The null and alternative hypotheses are defined as:

H_o: $\sigma_1 = \sigma_2 = \ldots = \sigma_k$

H_a: $\sigma_i \neq \sigma_j$ for at least one pair (i,j)

Given a variable Y with sample size N divided into k groups, where N_i is the sample size of the i-th group, the Levene's test statistic, W is defined as follows:

$$W = \frac{(N-k)}{(k-1)} \frac{\sum_{i=1}^{k} N_i \left(\overline{Z}_{i.} - \overline{Z}_{..}\right)^2}{\sum_{i=1}^{k} \sum_{j=1}^{N_i} \left(\overline{Z}_{ij} - \overline{Z}_{i.}\right)^2} \tag{3.7}$$

where Z_{ij} can have one of the following three definitions:

1. $Z_{ij} = \left|Y_{ij} - \overline{Y}_{i.}\right|$ where $\overline{Y}_{i.}$ = mean of the i-th subgroup
2. $Z_{ij} = \left|Y_{ij} - \tilde{Y}_{i.}\right|$ where $\tilde{Y}_{i.}$ = median of the i-th subgroup
3. $Z_{ij} = \left|Y_{ij} - \overline{Y}_{i.}'\right|$ where $\overline{Y}_{i.}'$ = 10% trimmed mean of the i-th subgroup

$\overline{Z}_{i.}$ are the group means of the $\overline{Z}_{ij}$ and $\overline{Z}_{..}$ is the overall mean of the $\overline{Z}_{ij}$ (i = 1, 2, 3 …, k and j = 1, 2, 3, …, k).

The null hypothesis is rejected if:

$$W > F_{(\alpha, k-1, N-k)}$$

Where W exceeds the upper critical value of the F distribution with k–1 and N–k degrees of freedom at a significance level of α.

3.4 Determining the influence of device width on operating speed

Given that the traffic calming devices studied in this research were installed either fully or partially across the width of a street, it was suspected that the width of a device with respect to the width of the road would have some degree of influence on the device operating speed, apart from the type of device and obviously, the height of vertical speed control devices.

Therefore, a study was carried out in order to relate device operating speed to the ratio of device width to road width. Twenty-one 100 mm speed humps, with widths ranging from 5.6 m to 10.4 m, were selected for this study. Road widths ranged from 8.1 m to 13.5 m.

Figure *3.7* shows typical layouts of a speed hump spanning across a street and another that spans partially across a street.

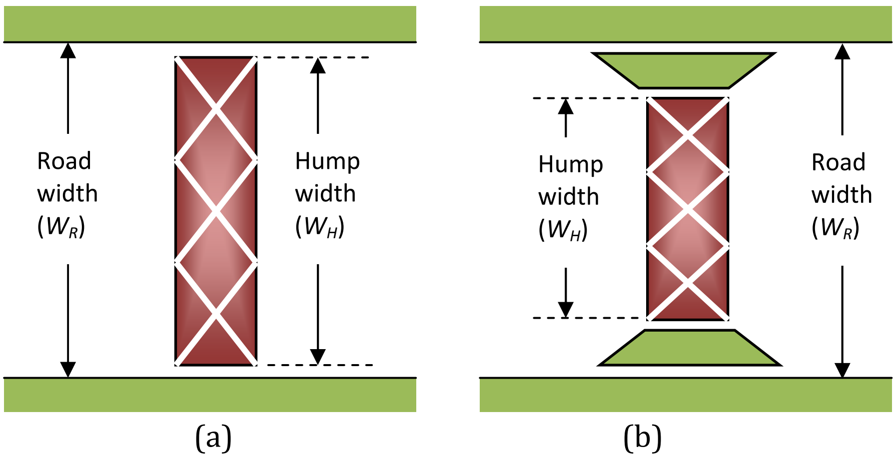


Figure 3.7 – Speed humps spanning (a) fully across and (b) partially across a street

Speed humps constructed partially across streets generally had islands or kerb extensions included in the design. The hump width to road width ratios (W_H/W_R) in these cases were considerably smaller than 1, ranging from 0.44 to 0.68.

For speed humps constructed fully across streets, the W_H/W_R ratios were between 0.90 and 0.92. It should be noted that a W_H/W_R ratio equal to 1 is not likely, due to the provision of drainage channels along the roadway periphery. Seeing as the width of a channel is approximately 0.5 m, therefore a speed hump constructed fully across a street will have a width that is 1.0 m less than the street width.

Regression analysis was performed to relate device operating speed (V_o) to the W_H/W_R ratio. V_o was taken as the 85th percentile speed recorded across 100 mm speed humps. Since the W_H/W_R ratio can never be zero, it was decided that the data be fitted into S-curve and power functions. The one that produced a better fit was selected to represent the relationship.

3.5 Modelling speeds on traffic-calmed streets

Speed models were developed for the purpose of estimating speed on the approach to a speed hump and between speed humps, using regression analysis for linear, logarithmic, power and S-curve functions (see *Table 3.3*). The functions that yielded the best curve-fit properties were selected to represent the relationship between the variables studied.

Table 3.3 – Basic equations for the functions tested

Function	**Basic Equation**
Linear	$Y = a + bX$
Logarithmic	$Y = a + b\log_{10}X$
Power	$Y = aX^b$
S-curve	$Y = \exp[a + (b/X)]$

where Y is the response variable, X is the predictor variable, *a* is the constant and *b* is the coefficient for the predictor variable

The response variable or dependent variable for the speed models was speed, V in km/h, while the predictor variable or independent variable was distance, L in metres, to or from the device. *Figure 3.8* provides an illustrative description of the segments studied, the variables considered for the models, and some terminology used.

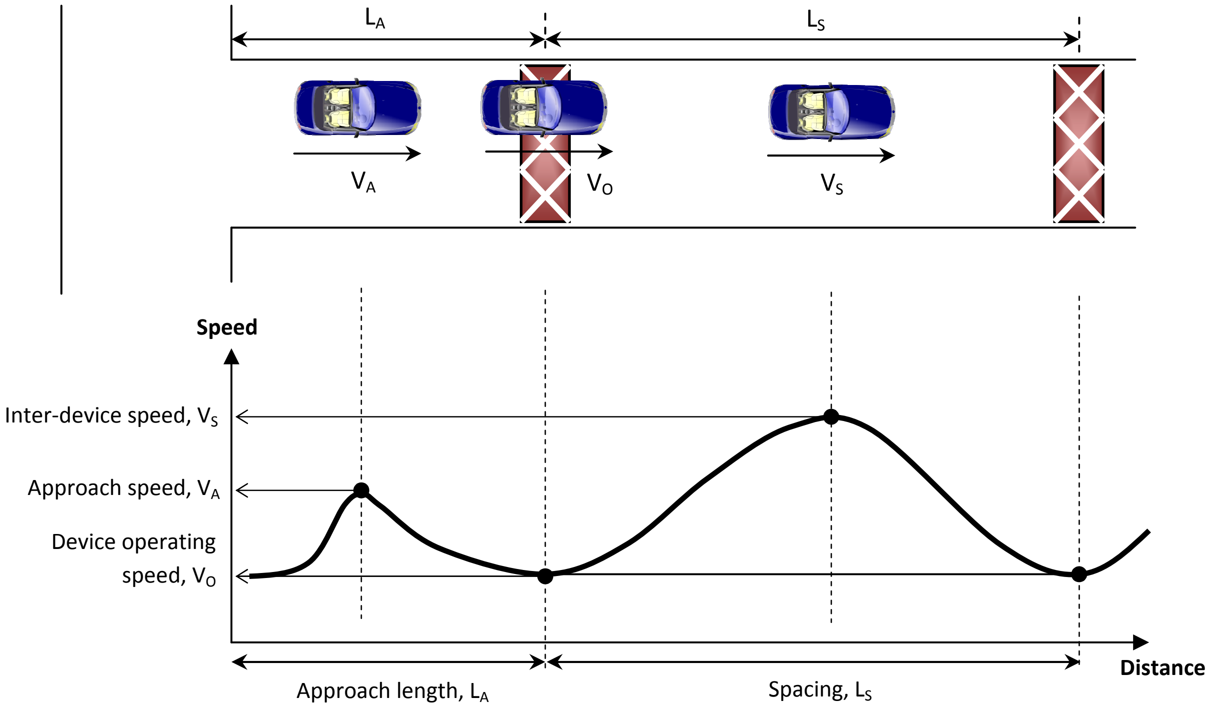


Figure 3.8 – Segments studied for the development of the speed models

3.5.1 Speed-distance models

In a speed-distance relationship, speeds (V) at medium to large distances were regarded as main outputs. Nevertheless, the value for the constant (y-intercept) was considered to be just as important, since it effectively represents the speed when distance is zero, i.e. at the device.

Consequently, device operating speed (V_o) was set as the constant, and the speed differential (ΔV), which is a function of length (L), was introduced as the predictor variable:

$$V = V_o + \Delta V \tag{3.8}$$

Hence, models having the form of equation 3.8 provide a more realistic representation of the speed-distance relationship from zero to large distances.

Speed on the approach

The basic equation used for relating approach speed to approach length is as follows:

$$V_{AE} = V_o + \Delta V_A \tag{3.9}$$

where V_{AE} is the estimated approach speed (km/h), V_o is the device operating speed (km/h) taken as the 85th percentile speed or mean speed recorded across devices, and $\Delta V_A = V_A - V_o$, where ΔV_A is the speed differential, which is dependent on approach length, L_A (m), and V_A is the approach speed taken as the highest observed 85th percentile speed (km/h) or mean speed (km/h) on the approach to a device.

Speed between devices

The basic equation used for relating inter-device speed to spacing between devices is given below:

$$V_{SE} = V_o + \Delta V_S \tag{3.10}$$

where V_{SE} is the estimated inter-device speed (km/h), V_o is the device operating speed (km/h) taken as the 85th percentile speed or mean speed recorded across devices, and $\Delta V_S = V_S - V_o$, where ΔV_S is the speed differential, which is related to spacing, L_S (m), and V_S is the inter-device speed taken as the highest observed 85th percentile speed (km/h) or mean speed (km/h) recorded between two successive devices.

3.5.2 Regression analysis

Regression analysis is a statistical procedure applied for modelling and analysing the relationship between a response variable (*Y*) and one or more predictor variables (*X*).

The objectives of regression are to determine if a relationship exists between *Y* and *X*, to study the form of the relationship curve, and to reflect on the reasons for the relationship. In most cases, the purpose is to make predictions of *Y* from *X* and the change in *Y* from a given increase in *X* with reasoning that changes in *Y* are caused by changes in *X* (Snedecor & Cochran, 1989).

The general model for bivariate regression (one response variable and one predictor variable), which is used extensively in this study, takes the form of:

$$Y_i = f(X_i) + \varepsilon_i \qquad (3.11)$$

where Y_i and X_i are the response and predictor variables respectively, $f(X_i)$ describes the function of the predictor X_i, and ε_i is the residual or error term at the i-th data point (i = 1, 2, 3, …, n) and n is the number of data points.

In fitting a regression model, four standard assumptions about the residuals were made:

1. At each value of the predictor variable, the distribution of the residuals is Normal.
2. The variance of the residuals at every set of values for the response variable is equal.
3. At every possible value of the predictor variables, the expected mean value of the residuals is equal to zero.
4. For any two cases, the expected correlation between the residuals should be equal to zero.

These assumptions give credence to the regression coefficients, hence making it possible to draw inferences from the association between *Y* and *X*.

3.5.3 *Interpreting the regression model output*

IBM SPSS Statistics 19 was used to perform curve estimation via regression analysis. The regression model output typically consists of three tables – Model Summary, ANOVA (Analysis of Variance) and Coefficients. An example of a regression model output is shown in *Table 3.4*.

Table 3.4 – Example of a regression model output

Model Summary

R	R-square	Adjusted R-square	Std. error of the estimate
0.692	0.479	0.442	2.630

ANOVA

	Sum of squares	df	Mean square	F	Sig.
Regression	88.987	1	88.987	12.868	0.003
Residual	96.813	14	6.915		
Total	185.800	15			

Coefficients

	Unstandardised coefficients		Standardised coefficients	t	Sig.
	B	Std. error	Beta		
Length	0.049	0.014	0.692	3.587	0.003
(Constant)	7.599	1.759		4.321	0.001

The Model Summary table provides values for the coefficient of determination (R^2) and the standard error of the estimate (SEE). The R^2 represents the goodness-of-fit of the model to the data, while the SEE is a measure of accuracy of predictions made using the regression model. Ultimately, a low SEE value is desired.

The ANOVA table indicates whether the regression model is able to predict the response variable significantly well. The F-statistic is used to compare the variability accounted for by the regression model with the remaining variation due to the model residuals. The null hypothesis of the test is that the coefficients of the regression model are zero, while the alternative hypothesis is that at least one of the coefficients is non-zero. The significance value (Sig.)

of the *F*-statistic is commonly used to make inference about the regression model. A significance value equal to or less than the α value (usually 0.05) is considered sufficient to reject the null hypothesis, i.e. the regression model is significantly good enough to predict the response variable.

The Coefficients table presents details of the regression equation, i.e. the coefficients for the predictor variables and the constant. The table also provides *t*-statistics and their associated significance values, which are used to make inferences on whether the coefficients are significantly different from zero. A significance value equal to or less than the α value is enough to reject the hypothesis that the coefficient is zero.

3.5.4 Selecting a regression model

The criteria for selecting the best-fit curve for any relationship between variables were set as follows:

1. The significance of the *F*-statistic should be equal to or less than 0.05 (the smaller it is the better).
2. The significance of the *t*-statistics should be equal to or less than 0.05 (the smaller it is the better).
3. The standard errors of the estimate and the coefficients should be low (the closer it is to zero the better).
4. The shape of the curve should ideally represent the spread of the data points.

The R^2 criterion was excluded because the R^2 does not provide an indication of a good fit to the data for nonlinear models. It is only when one has a linear model with a constant that the R^2 genuinely represents the proportion of variation explained by the model (Ratkowsky, 1990).

3.6 Studies on safety impact of traffic calming

Before-and-after crash analysis was employed for the purpose of investigating the impact of traffic calming on road safety. NZTA's Crash Analysis System (CAS) was used for obtaining crash information and mapping crash locations.

The first study involved 28 randomly selected traffic-calmed streets spread across Christchurch, while the second was a study of treated and untreated streets in close proximity that was carried out in Mairehau. The latter was conducted to examine the area-wide effects of traffic calming, and to investigate whether crash trends were similar on treated and untreated streets.

3.6.1 The study of traffic-calmed streets

Crash data for 28 traffic-calmed streets were analysed. These data were for the pre-installation and post-installation periods. Crashes on the streets were grouped into two main categories; intersection crashes and mid-block crashes.

Intersection crashes were taken as crashes occurring within 30 m of an intersection. These crashes were further split into two types; street-end crashes and side road crashes.

Street-end crashes included crashes involving motorists, pedestrians or cyclists entering or exiting the street at either of its ends, while side road crashes included crashes occurring where a side road intersects the street (see *Figure 3.9*).

Mid-block crashes were all other crashes occurring at least 30 m from an intersection.

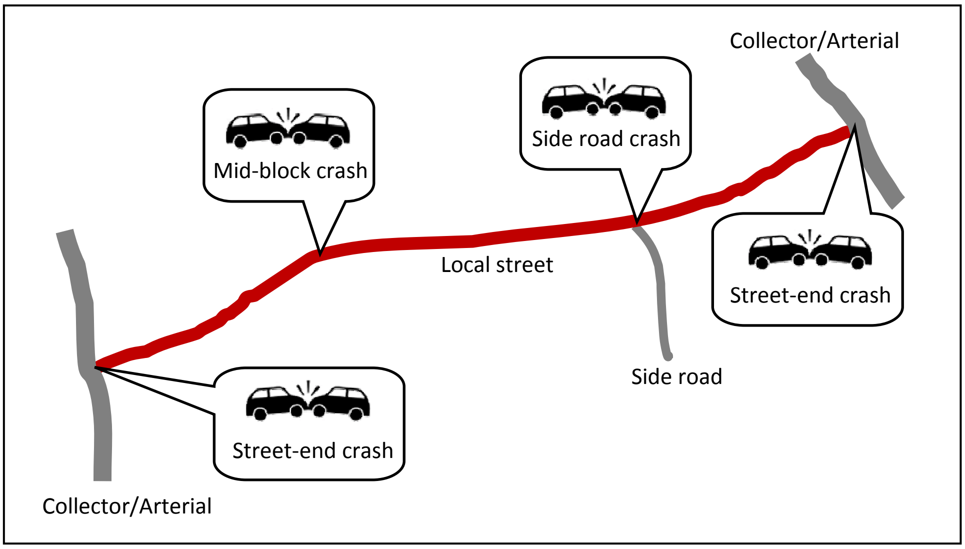


Figure 3.9 – Crash types considered for analysis

The same number of years of crash data was used for both 'before' and 'after' periods (in years) at each location, but different periods were used for different locations. Naturally, streets that were recently calmed had shorter analysis periods. Therefore, the crash rate, i.e. number of crashes per year, was set as the safety impact descriptor.

Given that pedestrians and cyclists, apart from motorists, are also affected by traffic calming measures, the study also looked into crashes involving these vulnerable road users.

A crash may be the result of one or more factors. Therefore it was important to study the causative factors cited in all crashes. The objectives were to determine the main factors for the crashes, and to investigate whether roadway factors, as a result of the installation of physical devices, contributed to the crashes.

3.6.2 *The Mairehau area-wide study*

The study was conducted in the suburb of Mairehau, where traffic calming treatments were implemented on eight streets, collectively known as the Flockton Cluster, circa 2006 – 2007. Apart from the treated streets, another 22 untreated streets were also included in the study. The study area, bounded by four arterials, is shown in *Figure 3.10*.

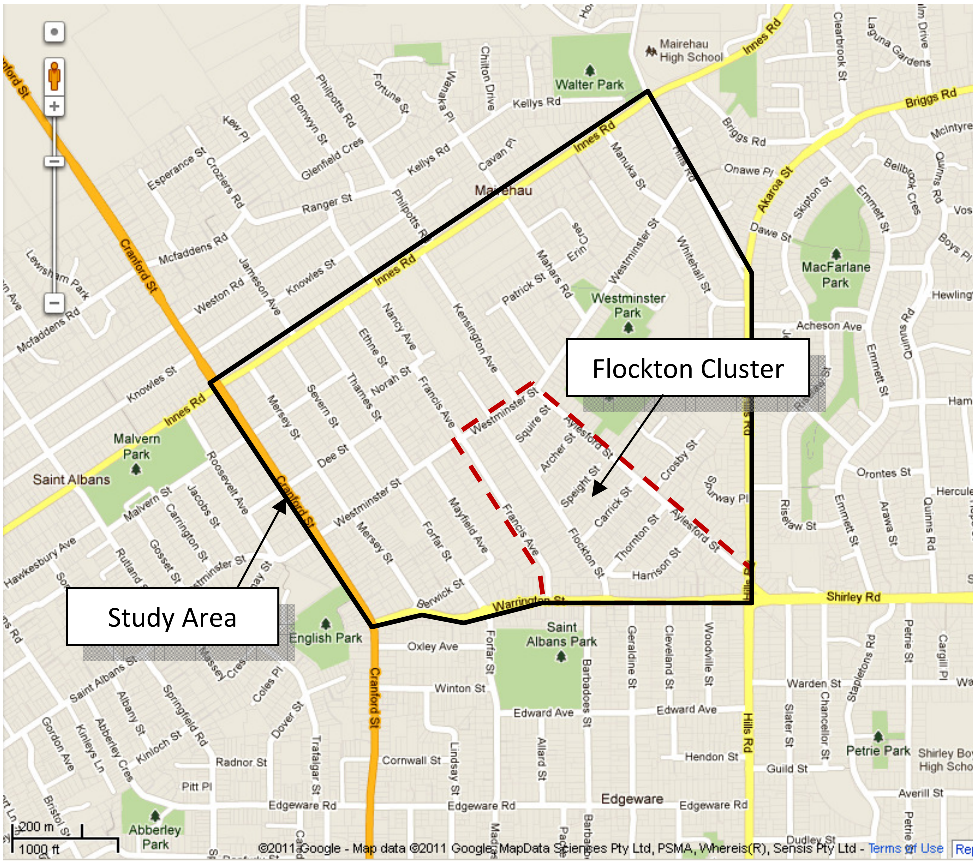


Figure 3.10 – Study area in Mairehau

Traffic calming devices implemented on the treated streets included mid-block treatments such as speed tables and narrowings, and entrance treatments such as textured surfacing and narrowings (see *Table 3.5*). The list of the 22 untreated streets is provided in *Appendix B*.

Table 3.5 – Treated streets in the Flockton Cluster

Street Name	Treatment	
	Mid-block	Entrance
Aylesford Street	Speed tables (5)	Speed hump and narrowing
Francis Avenue (East)	Speed tables (3)	Speed hump and narrowing, Textured surfacing
Flockton Street	2-lane narrowing (2)	Narrowing, Speed hump and narrowing
Carrick Street	1-lane narrowing (3)	
Thornton Street	1-lane narrowing (3)	
Archer Street		Textured surfacing
Speight Street		Textured surfacing
Squire Street		Textured surfacing and narrowing

Note: The number in parenthesis indicates the number of devices

Crash data from 2003 to 2005 ('before' period) and 2008 to 2010 ('after' period) were retrieved for the comparative analysis. The safety impact descriptor was crash rate per site, i.e. number of crashes/year/site.

The factors cited in crashes were also studied, with comparisons being made between pre-installation and post-installation periods, and between treated and untreated streets.

3.7 Site selection, experimental setup and data collection for noise studies

Five residential streets in Christchurch were chosen for the studies on noise produced by vehicles on traffic-calmed streets. The streets were Lochee Road, Wadeley Road, Wilfrid Street, Chilcombe Street and Hamilton Avenue. All streets were in Ilam, except for Lochee Road which was located in Upper Riccarton.

The collection of noise data was conducted in two phases; the first being the measurement of noise next to speed humps and a flat section of road, and the second involved the measurement of idling engine noise.

Given that people's response to noise from traffic flows less than 2,000 AADT is mostly individual vehicle noise as a transient maximum sound level (NZS 6801:2008), L_{AFmax} was chosen as the noise descriptor.

A Brüel & Kjær Type 2250 sound level meter (see *Figure 3.11*) was used to measure maximum A-frequency weighted, fast-time-weighted noise levels (L_{AFmax}) produced by vehicles.

Figure 3.11 – Brüel & Kjær Type 2250 sound level meter

3.7.1 Noise measurement next to speed humps and a flat section of road

Vehicle noise was measured next to a 75 mm Watts profile speed hump on Lochee Road, a 100 mm Watts profile speed hump on Wadeley Road and a flat section on Lochee Road. For the flat section, noise was measured mid-way between two speed humps spaced 100 m apart.

The microphone was positioned at a distance of 7.5 m from the centre of the nearside travel lane, 1.2 m from the ground, and at least 3.5 m from reflective surfaces, such as walls or fences. This was in accordance with ISO 11819-1:1997 and NZS 6801:2008. Noise data were also collected for opposing traffic on the farside travel lane (11.7 m to 13.6 m from the microphone). For the purpose of determining vehicle speed and identifying vehicle type, a video recorder was used concurrently. *Figure 3.12* shows the experimental setups. Photographs can be found in *Appendix C*.

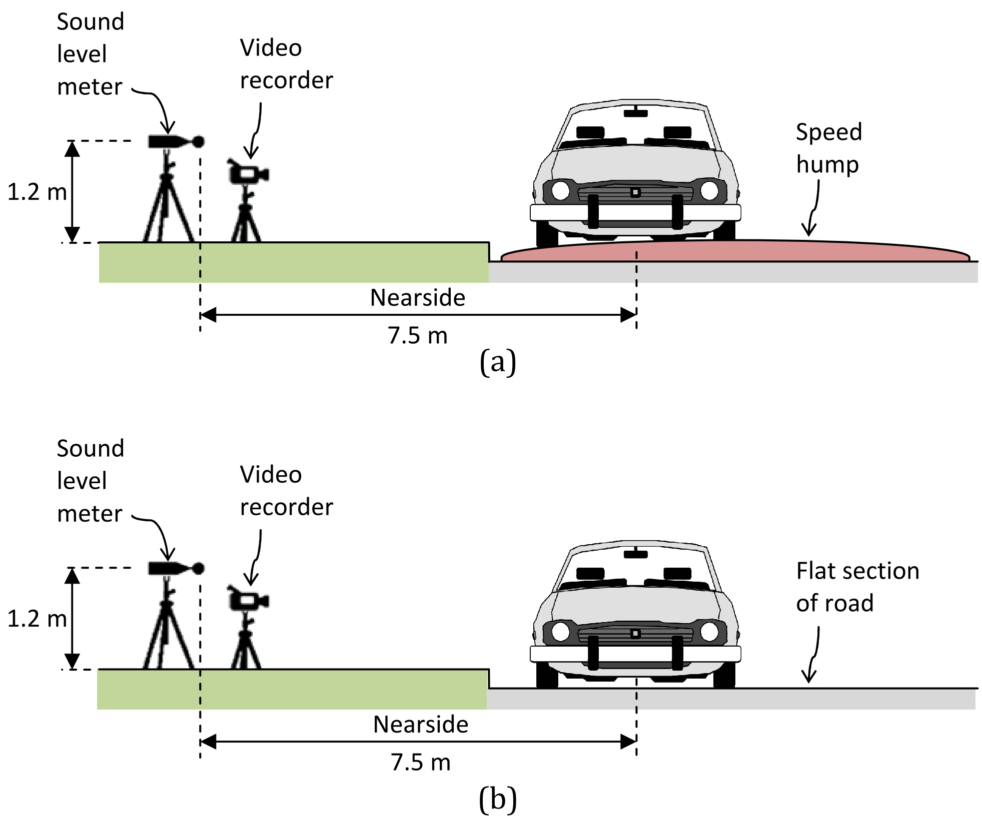


Figure 3.12 – Experimental setup for measurement of vehicle noise next to (a) a speed hump and (b) a flat section of road

The method for measurement was based on the Statistical Pass-By (SPB) method prescribed by ISO 11819-1:1997. This method is intended for measuring noise from road-tire interactions for vehicles travelling at constant speed (50 km/h and above).

It should be noted that the method used in this study, which involved the measurement of noise levels for vehicle pass-bys (where vehicles decelerate at the observation point), was an adaptation of the SPB method.

The method involved the measurement of maximum A-weighted sound pressure levels and corresponding vehicle speeds of a statistically significant number of individual pass-bys at a specified roadside location.

The vehicles studied were classified into two categories; light vehicles and heavy vehicles. Passenger cars, multipurpose vehicles (MPV), sports utility vehicles (SUV) and vans were considered as light vehicles, while trucks and buses were grouped as heavy vehicles. Given that the volume of heavy vehicles using the residential streets were not more than 2%, the study was focused mainly on light vehicles. For the analysis of noise-speed relationship, at least 100 vehicle pass-bys were required.

Vehicles towing trailers, although small in numbers, were also studied. This was founded on observations that the trailers produced loud noises when crossing the speed humps.

All measurements took place on clear, dry weekdays with moderate temperatures and calm wind conditions, during the period 12:00 PM to 2:00 PM. The evening peak was not considered because activities among residents (i.e. walking, jogging, playing, talking) were higher, which could have resulted in sounds that contributed to additional background noise.

However, background noise during the data collection was inevitable. These included sounds originating from distant traffic, people talking and mowing their lawns, and animal sounds, particularly birds.

Background noise was measured when no traffic was present. This was done to ensure that sound pressure levels from activities other than traffic on the road site were at least 10 dBA below the maximum sound level during pass-bys recorded from the vehicles (ISO 11819-1:1997).

Occasionally, noise disruptions came from aircraft flyovers, sudden wind gusts and blaring music from vehicles. Obviously, measurements that were affected by these disruptions and other extreme background noise were discarded.

3.7.2 Measurement of idling engine noise

The idling engine noise, which is the noise produced by stationary vehicles (zero speed) with their engines left running, was sought for the development of noise prediction models.

Hence, 20 vehicles were sampled for the measurement of maximum noise levels emitted by vehicles in their 'idle' state. The study was conducted on Wilfrid Street, Chilcombe Street and Hamilton Avenue. Drivers volunteered to keep their engines running either after parking or before un-parking while the aforesaid measurements were recorded.

All conditions for noise measurement, as described in section 3.6.1, were matched in this study. The experimental setup is shown in *Figure 3.13*.

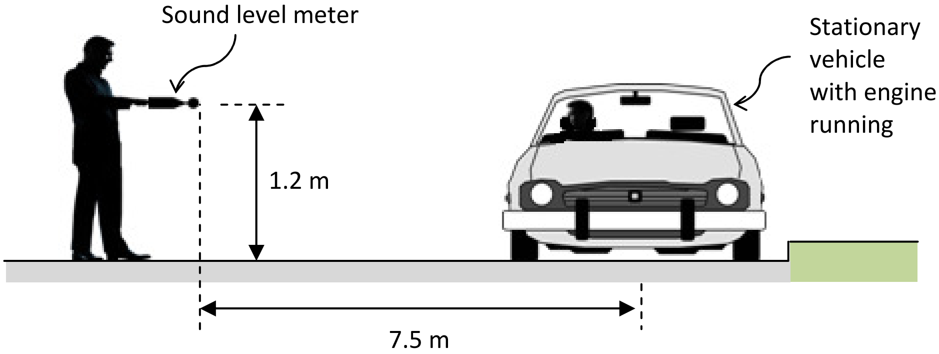


Figure 3.13 – Experimental setup for measurement of idling engine noise

The idling engine noise was determined by calculating the mean of the maximum noise levels produced by stationary vehicles with their engines left running.

3.8 Modelling vehicle noise emissions on traffic-calmed streets

The speed model concept described in section 3.5 was applied in the development of models relating noise with speed, except that the idling engine noise was set as the constant (at zero speed) and the noise differential was used as the predictor variable.

The functions considered for the noise differential models were S-curve, logarithmic, power and linear functions. The curves were estimated by means of regression analysis. The methods for running the regression analysis and selecting the regression model, as discussed in sections 3.5.2 to 3.5.4, also apply here.

For the purpose of correlating noise levels emitted by light vehicles traversing a speed hump or a flat section of road with vehicle speed, the following basic equation was used:

$$L_{ME} = L_{idle} + \Delta L_M \tag{3.12}$$

where L_{ME} is the estimated maximum noise level (dBA), L_{idle} is the mean of maximum noise levels (dBA) produced by stationary vehicles with engines left running, and $\Delta L_M = L_M - L_{idle}$, where ΔL_M is the noise differential, which is a function of vehicle speed, V (km/h), and L_M is the maximum noise level or L_{AFmax} (dBA) produced by vehicles in motion.

4 Research Results

This research was designed to investigate the consequences of traffic calming on traffic speed, safety and noise in residential areas. The analysis of speed data yielded findings that explain how speed control devices affect drivers' choice of speed, and the importance of appropriate spacings for devices used in sequence in regulating approach and inter-device speeds, while the analysis of before-and-after crash data assessed the level of influence that traffic calming has on road safety. Lastly, the analysis of noise data provided some understanding about the association of speed humps with noisiness. The following sections comprehensively report the results of this research.

4.1 Device operating speed

The operating speed of a traffic calming device was taken as the 85th percentile speed recorded at the device. The operating speed serves as an indicator of the effectiveness of calming devices. Although the physical geometry of each device influences the operating speed, it is likely that the operating speed is also influenced by the speeds on the approaches. It should be noted that the prevailing speed limit for all traffic-calmed streets studied was 50 km/h.

An effective device will have an operating speed close to or smaller than the target speed. The target speed for vehicles crossing vertical speed control devices is often 20 km/h, as indicated by advisory signs. The target speed for horizontal speed control devices is typically higher. However, advisory speed signs are usually not provided for these devices. *Table 4.1* shows the device operating speed for the seven types of mid-block single devices covered in this research, while *Table 4.2* provides the descriptive statistics.

While the speed hump came close to attaining the 20 km/h target speed, the other devices did not exhibit a similar effect. Interestingly, the speed table did not perform as well as expected, despite the table being 20 mm higher than the hump. This was probably due to the extensive flat top and ramps on both ends, which provided a smoother ride compared to the speed hump.

Table 4.1 – Operating speeds of single devices

Device	Device Dimensions	Operating Speed (km/h)
Speed hump	Watts profile 100 mm (H) x 3.7 m (L) x 5.8 m (W)	21.9
Speed table	120 mm (H) x 5.8 m (L) x 8.3 m (W) 1:8 ramp gradient	35.0
Angled slow point *One-lane, flush*	5.1 (L) x 3.0 (W)	39.5
Angled slow point *One-lane, raised*	50 mm (H) x 16.0 m (L) x 3.2 m (W) 1:20 ramp gradient	30.0
Narrowing *One-lane, flush*	11.6 m (L) x 3.6 m (W)	50.8
Narrowing *One-lane, raised*	50 mm (H) x 3.0 m (L) x 4.6 m (W) 1:40 ramp gradient	44.7
Narrowing *Two-lane, flush*	6.0 m (L) x 5.6 m (W)	50.8

H, L and W denote constructed height, length and width respectively.

Table 4.2 – Descriptive statistics of speeds recorded at single devices

Device	Speed (km/h)						Sample size
	Mean	Std Error	Std Dev	Range	Min	Max	
Speed hump	17.6	0.7	5.3	31.1	6.1	37.2	62
Speed table	24.5	1.1	9.5	44.1	5.8	49.9	77
Angled slow point *One-lane, flush*	33.5	0.4	6.9	39.6	16.2	55.8	311
Angled slow point *One-lane, raised*	23.3	0.5	7.3	40.4	4.6	45.0	240
Narrowing *One-lane, flush*	44.2	0.6	7.3	43.9	30.3	74.2	147
Narrowing *One-lane, raised*	34.4	0.9	10.5	49.2	9.7	58.9	138
Narrowing *Two-lane, flush*	43.5	0.6	7.1	39.1	24.3	63.4	128

The operating speeds of flush narrowings were considerably higher than other devices and close to the travelling speeds on unimpeded segments of the streets, indicating that these devices are ineffective.

One-lane angled slow points performed better than narrowings, in terms of lowering speeds. The raised angled slow point registered a lower operating speed, which was even lower than what the speed table produced.

For the study that involved multiple devices, 1,239 vehicle speeds were recorded over 21 speed humps and another 1,084 vehicle speeds were recorded over 14 speed tables. The device operating speeds were higher than the ones previously obtained for single devices. For the speed humps (100 mm in height), the device operating speed was established as 29.1 km/h, while for the speed tables (75 mm) it was 37.2 km/h. *Table 4.3* summarises the descriptive statistics for both devices.

The device operating speeds for individual speed humps ranged between 21.9 and 33.9 km/h, while for speed tables, the speeds were between 27.9 and 45.1 km/h.

Table 4.3 – Descriptive statistics of speeds (in km/h) recorded at devices used in a series

Statistical Parameters	Speed Humps	Speed Tables
85^{th} Percentile	29.1	37.2
Mean	22.3	27.2
Standard error	0.2	0.3
Standard deviation	6.8	9.2
Range	45.2	53.9
Minimum	6.1	5.8
Maximum	51.3	59.7

From a study that involved two speed hump variants, i.e. 75 mm and 100 mm high humps on Lochee Road and Wadeley Road respectively, the device operating speed for the 75 mm hump was 42.2 km/h while for the 100 mm hump it was much lower, at 30.5 km/h (see *Table 4.4* for the descriptive statistics).

Table 4.4 – Descriptive statistics of speeds (in km/h) recorded at 75 mm and 100 mm speed humps

Statistical Parameters	75 mm Speed Hump	100 mm Speed Hump
85^{th} Percentile	42.2	30.5
Mean	30.4	25.5
Standard error	0.9	0.4
Standard deviation	10.3	5.6
Range	53.4	31.2
Minimum	9.9	12.7
Maximum	63.3	43.8

The device profile (i.e. length, width, and height), the available distance leading up to the device and the approaching speed have considerable influence over the device operating speed. These will be discussed in the subsequent sections.

It is also believed that when devices are used in sequence on a street, what drivers see in front of them (some may even perceive it as the number of 'obstacles' to clear) may, to a certain degree, govern their choice of speed when traversing the devices. This hypothesis was tested using regression analysis to relate device operating speed (of the first speed hump) with the number of speed humps on the street. Based on the output shown in *Table 4.5*, it was found that there was a very weak relationship (R^2 = 0.027) between the two variables. Hence, it could not be concluded that the number of devices had actually influenced the device operating speed at the study sites.

Table 4.5 – Output summary for analysis on relationship between device operating speed and number of speed humps

Model Summary				
R-square: 0.027	Standard Error: 3.368			
ANOVA				
F-statistic: 1.186	Significance: 0.282			
Coefficients				
	Coefficient	Standard Error	t-statistic	Significance
Constant	26.357	1.198	21.997	0.000
Number of speed humps	0.684	0.628	1.089	0.282

4.2 Speed profiles

Speed profiles for single and multiple devices were produced from aggregated values, i.e. 85th percentile and mean speeds. The plots of individual vehicle speed recordings can be found in *Appendix D*.

It should be noted that zero distance indicates the point of observation and not the street entry. The observation points were at least 30 m from the street entry, depending on the availability of space and geometry of the street.

The length of the profile depended on the street length. Longer profiles were generally obtained for longer streets.

4.2.1 Speed profiles for single devices

The speed profiles produced for the single devices are shown in *Figures 4.1* to *4.7.*

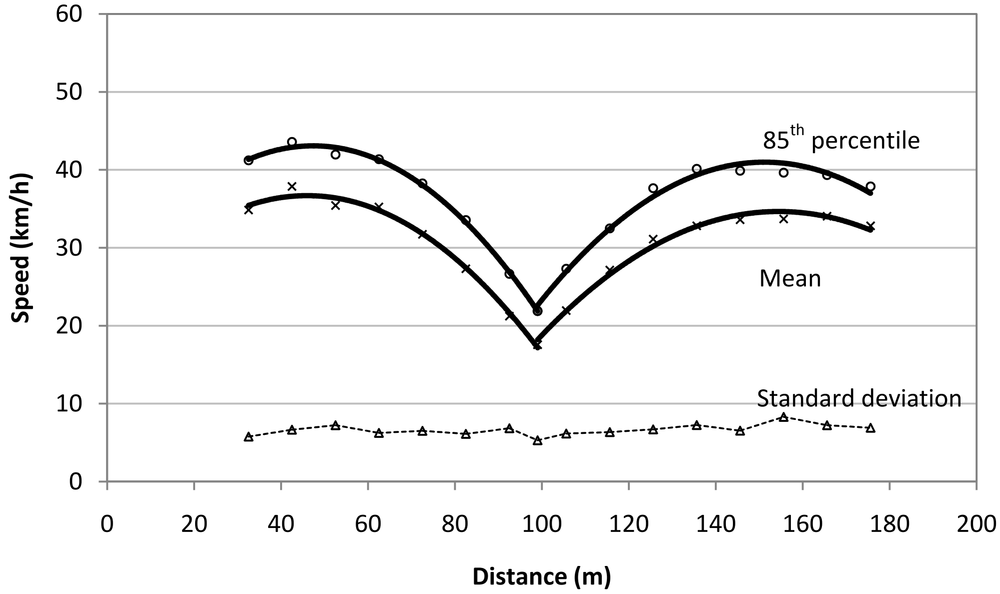


Figure 4.1 – Speed profiles for the speed hump

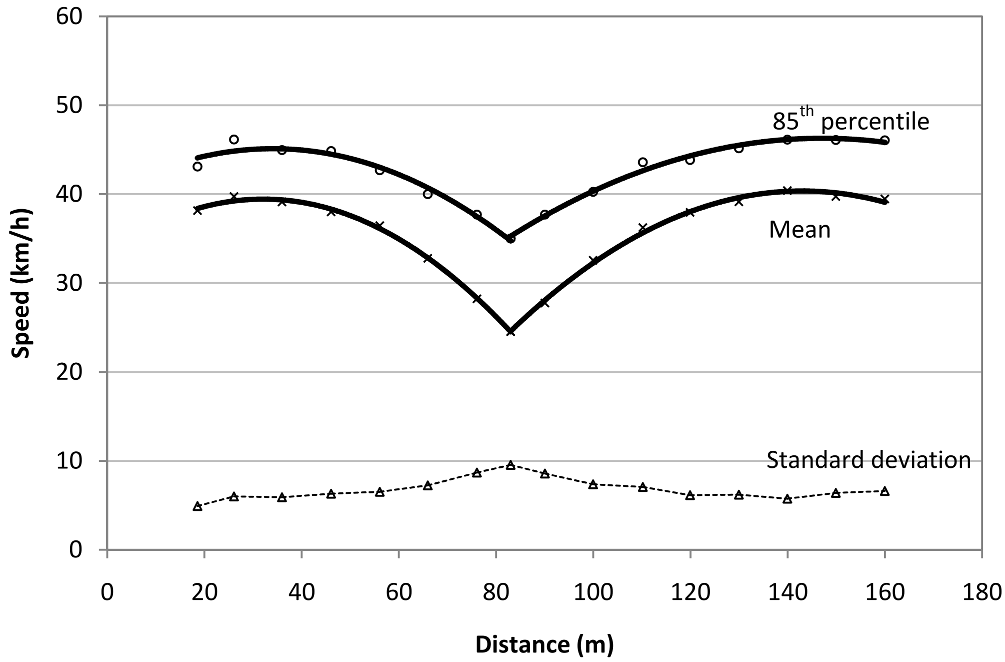


Figure 4.2 – Speed profiles for the speed table

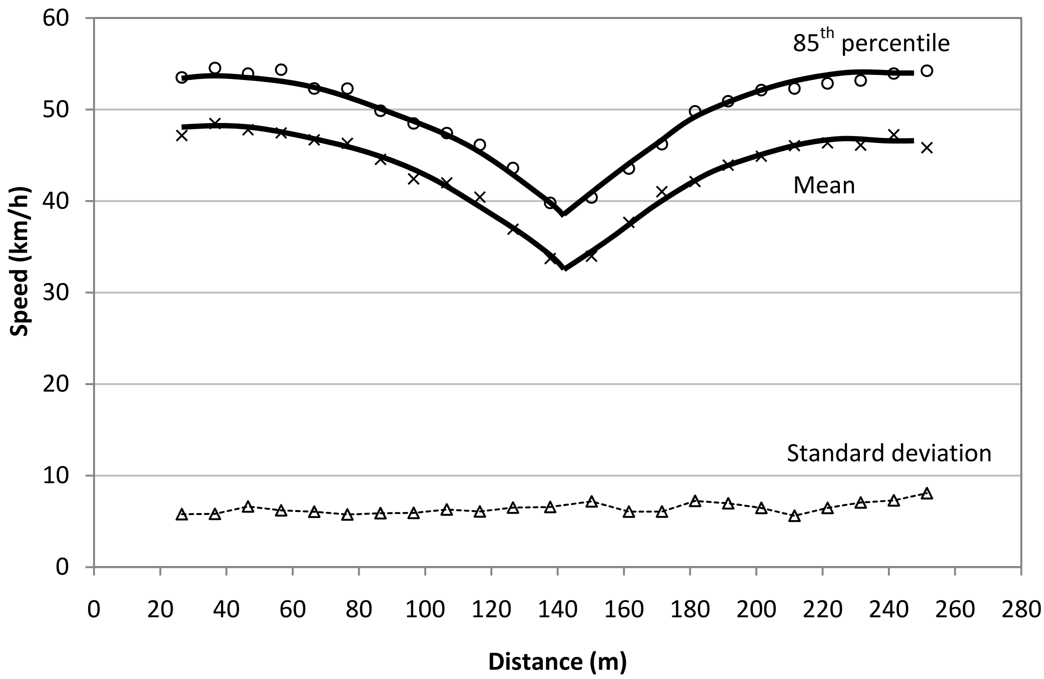


Figure 4.3 – Speed profiles for the one-lane flush angled slow point

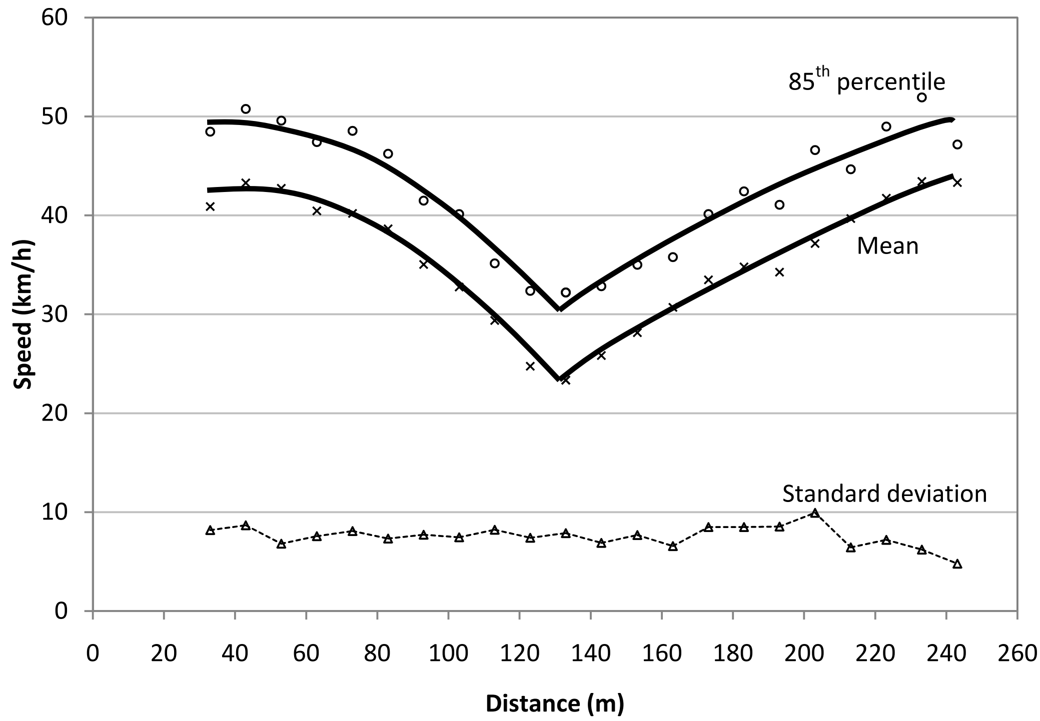


Figure 4.4 – Speed profiles for the one-lane raised angled slow point

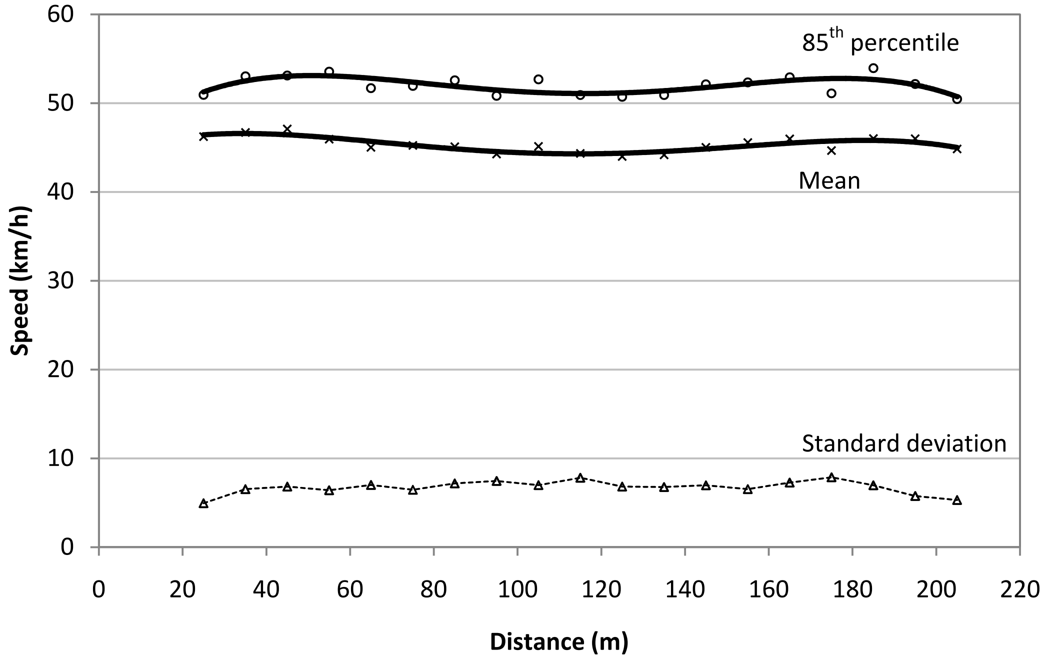


Figure 4.5 – Speed profiles for the one-lane flush narrowing

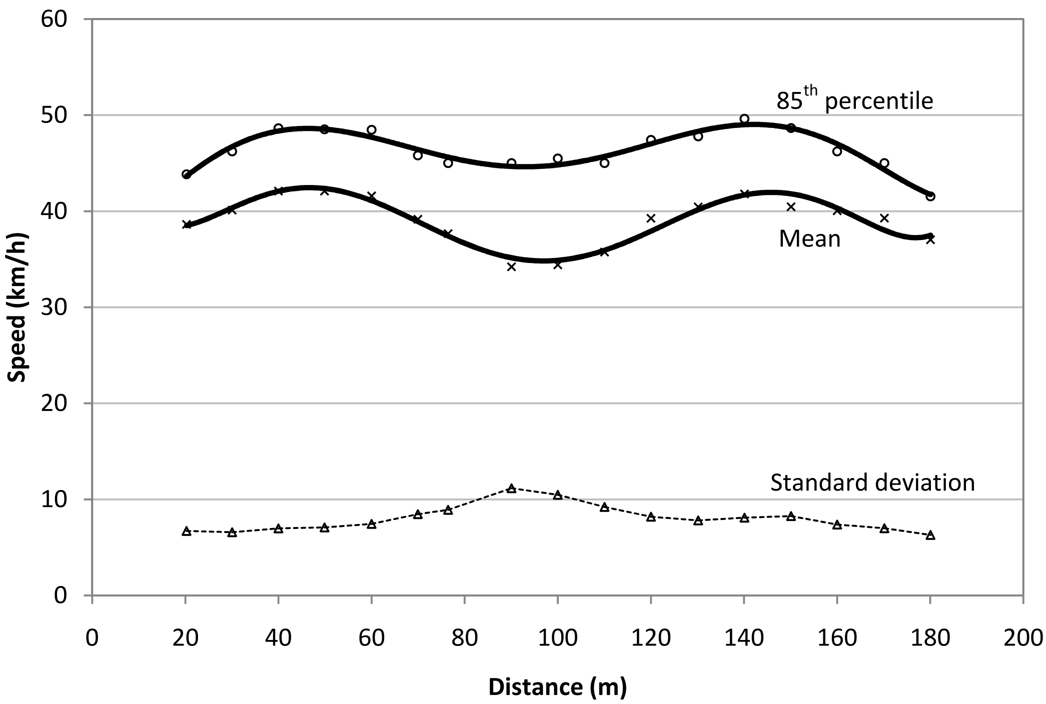


Figure 4.6 – Speed profiles for the one-lane raised narrowing

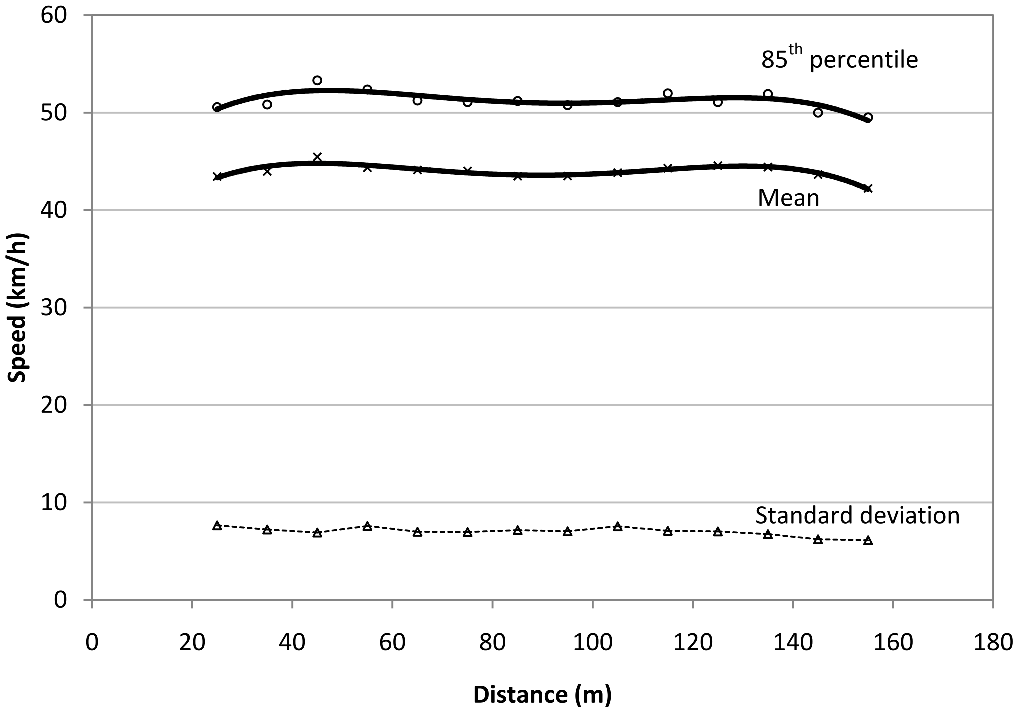


Figure 4.7 – Speed profiles for the two-lane flush narrowing

In order to obtain the shape of the profiles, polynomial curve fitting was performed, with two polynomials used where there was a pronounced dip in the values.

In general, the 85th percentile and mean speed profiles produced for vertical speed control devices featured significant dips where the devices were located. The speed curve obtained on either side of the vertical speed control devices followed a quadratic shape rather closely.

In contrast, the general shape of speed profiles for horizontal devices was flatter, having a less pronounced dip. This was due to the relatively small drops in speeds observed at the devices.

A slight dip, however, was observed when an element of vertical deflection was introduced together with a horizontal deflection (see *Figures 4.5* and *4.6*). However, the speed reduction at the combined device was smaller than for the speed hump and speed table due to an inferior height of 50 mm.

4.2.2 Speed profiles for multiple devices

The speed profiles for traffic calming schemes that used multiple speed humps and speed tables at varied spacings are shown in *Figures 4.8* to *4.15*. The fitted curves between the device locations and the approach to the devices from the street entries were also found to be approximately quadratic in form.

The profiles revealed a common trait in the change in speed as spacings and approach lengths changed. It was observed that larger spacings and approach lengths produced higher speeds. However, the maximum inter-device and approach speeds were not necessarily the same when spacing and approach lengths were about equal (refer to *Figure 4.8*).

For speed humps, the maximum 85th percentile inter-device speed was nearly 10 km/h lower at the 95 m spacing than the ones recorded at 150 m and 200 m spacings, which were almost identical. This suggests that spacings below 100 m produce a more desirable speed level, and that there seems to be a limit for inter-device speed at large spacings, whereby drivers are generally not inclined to excessively speed between devices.

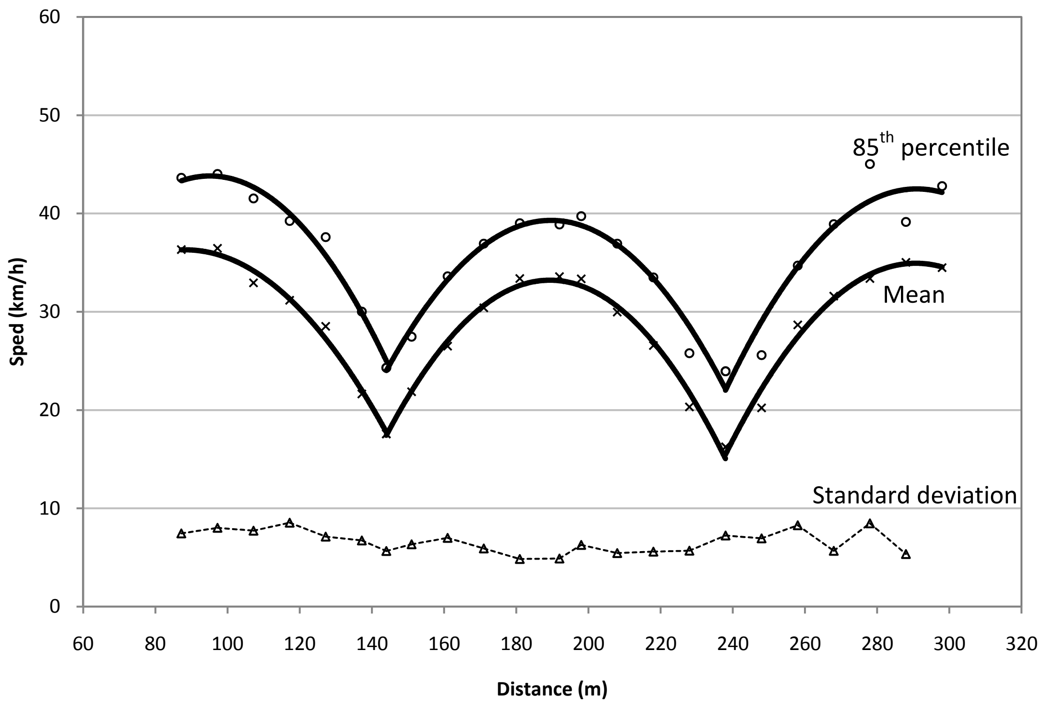


Figure 4.8 – Speed profiles for two speed humps spaced 95 m apart

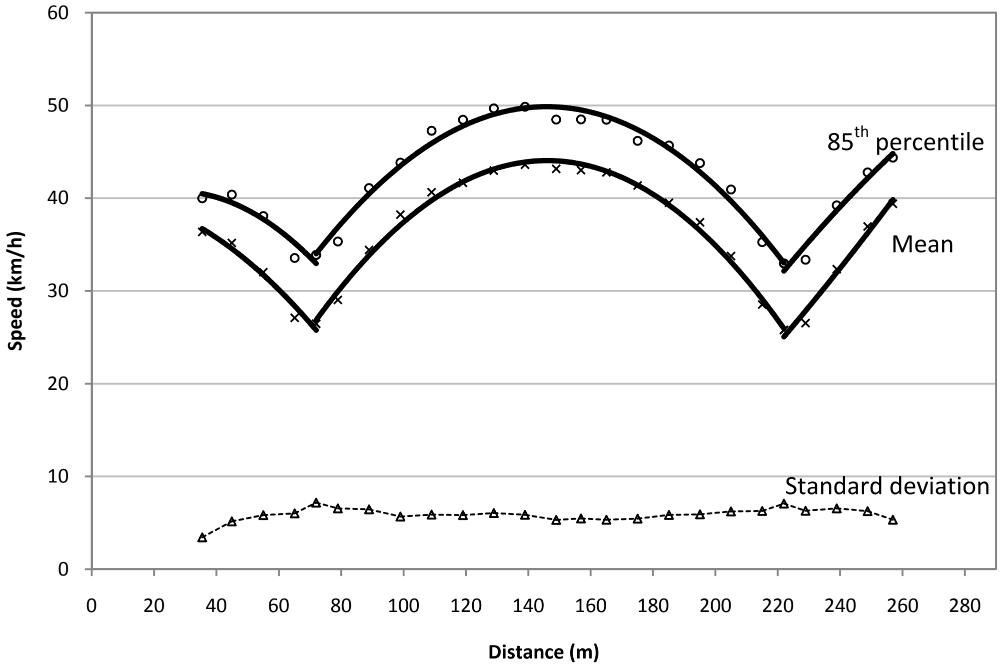


Figure 4.9 – Speed profiles for two speed humps spaced 150 m apart

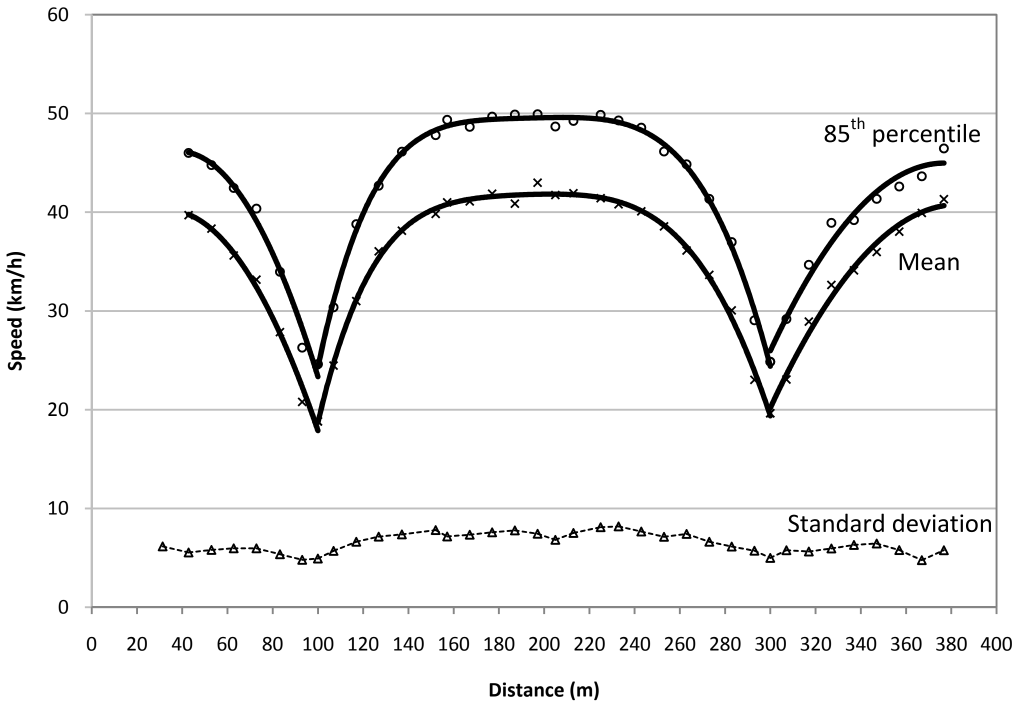


Figure 4.10 – Speed profiles for two speed humps spaced 200 m apart

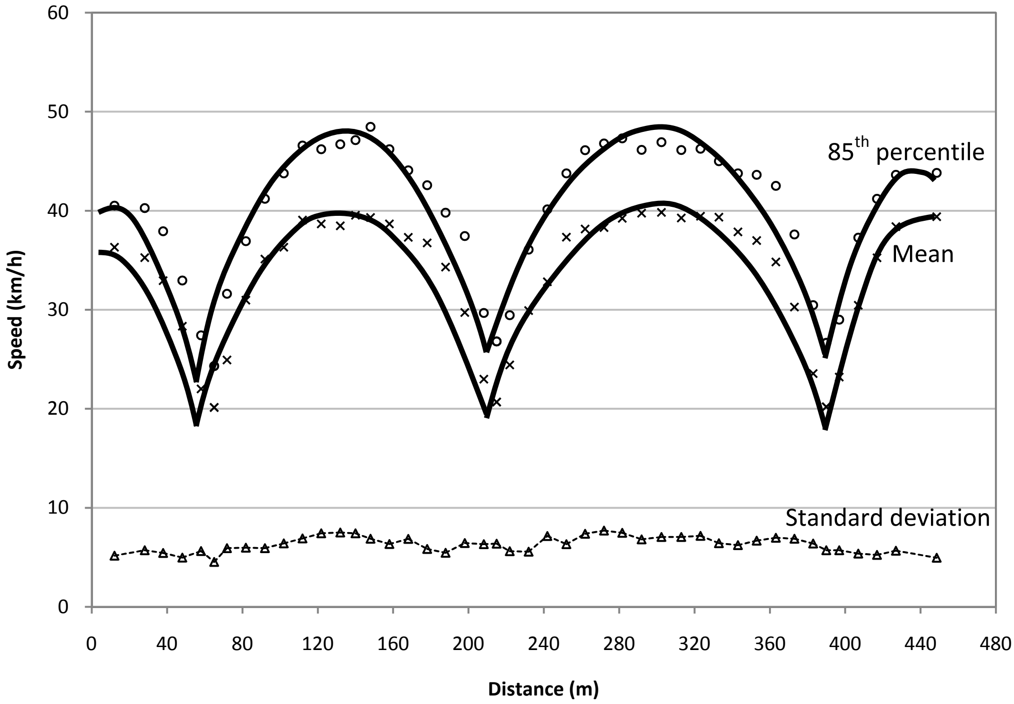


Figure 4.11 – Speed profiles for three speed humps spaced 150 m and 175 m apart

The speed profiles for speed tables used in a series were noticeably different from the ones for speed humps in terms of the magnitude and range of speeds. Speeds were smaller in range but higher in magnitude than for speed humps. They were quite similar in shape to the ones produced for speed humps.

Just like for the speed humps, larger spacings and approach lengths resulted in higher speeds. However, there was some inconsistency in speeds observed at larger spacings, particularly when three speed tables were used (see Figure *4.15*).

Although the spacings were not very different from each other (145 m and 155 m), the observed maximum 85th percentile speeds differed by about 2 km/h, and were in excess of 50 km/h. This was in contrast to the sub-50 km/h observed at the street with two speed tables spaced 150 m apart.

A further analysis was carried out to associate spacing of speed humps and speed tables on inter-device speed. The findings are explained in Section 4.9.

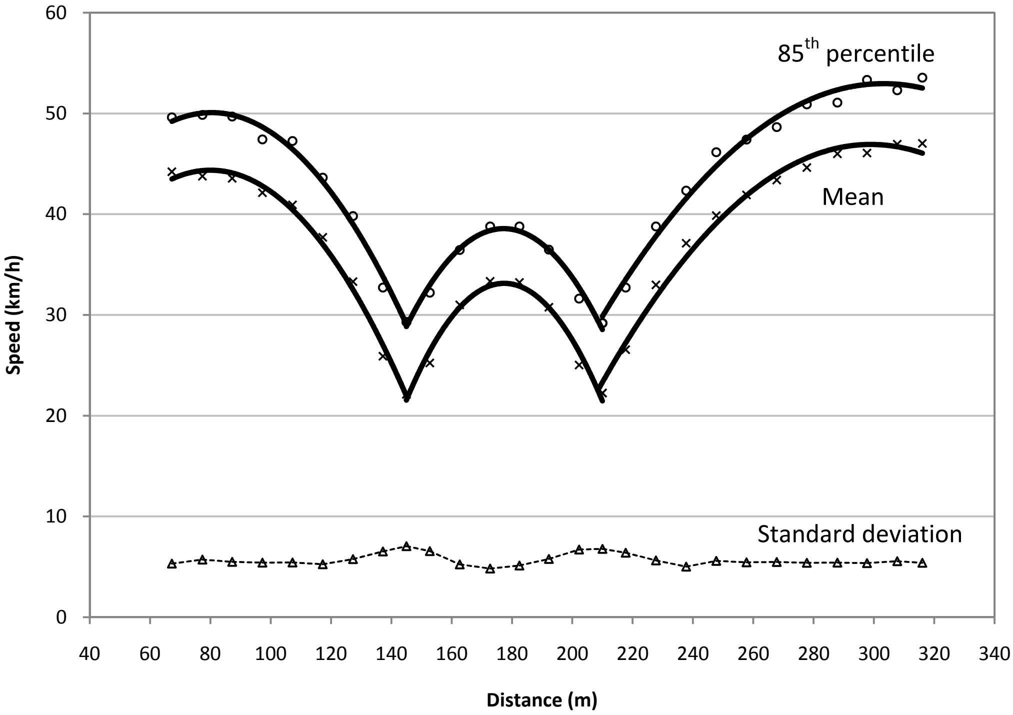


Figure 4.12 – Speed profiles for two speed tables spaced 65 m apart

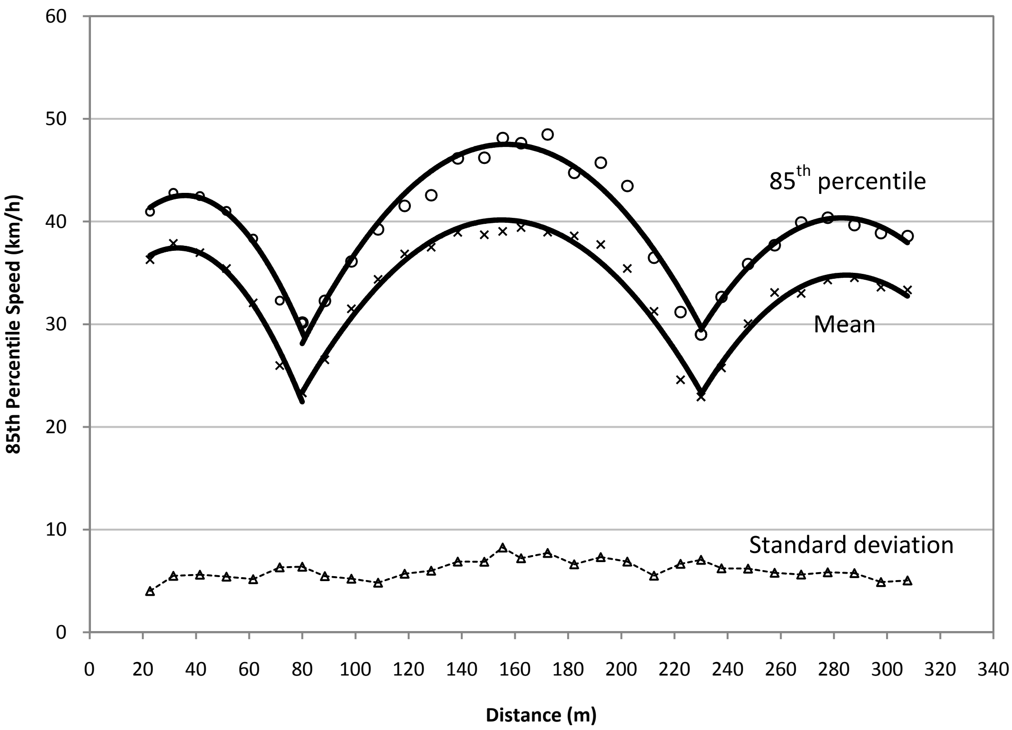


Figure 4.13 – Speed profiles for two speed tables spaced 150 m apart

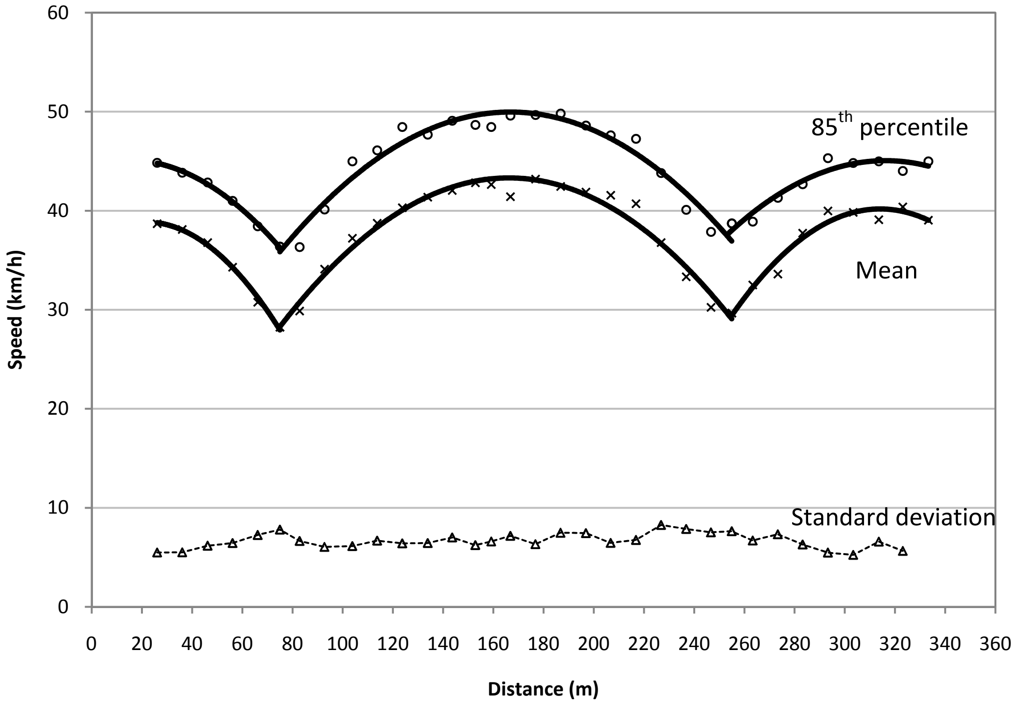


Figure 4.14 – Speed profiles for two speed tables spaced 180 m apart

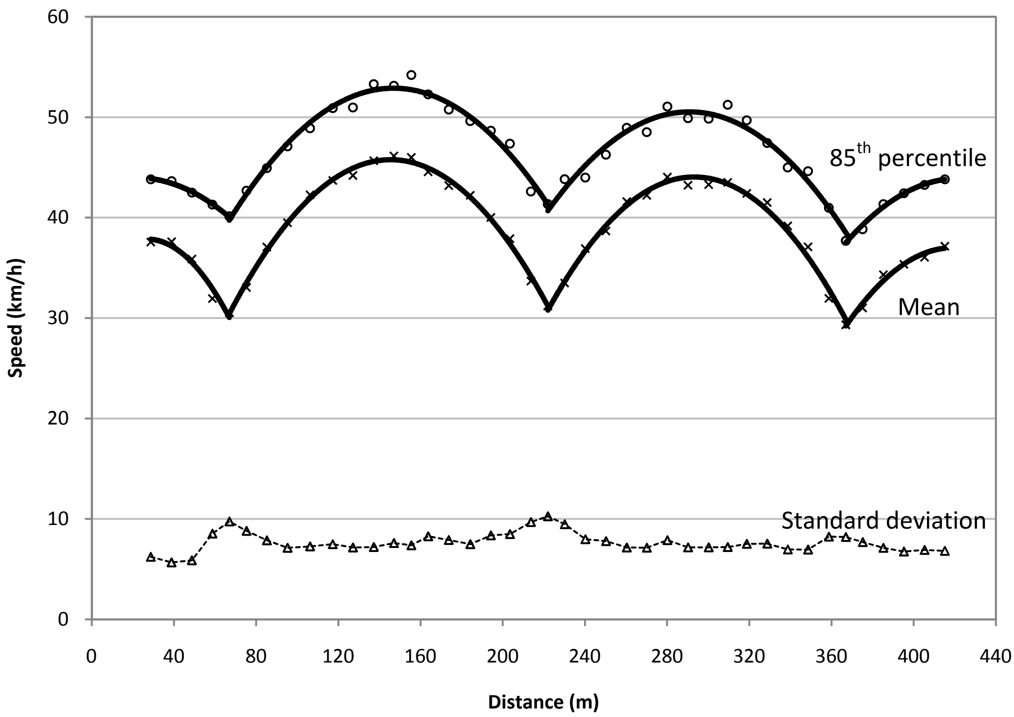


Figure 4.15 – Speed profiles for three speed tables spaced 145 m and 155 m apart

4.2.3 Speed profiles for drivers grouped according to initial speed

Given that speeds of individual drivers were measured and their respective profiles obtained, it was therefore possible for the drivers to be grouped according to initial speed.

By analysing the speed profiles of drivers grouped by initial travelling speed, it was found that speed levels had reduced after drivers traversed speed control devices that had the element of vertical deflection (see Figures *4.16* and *4.17*).

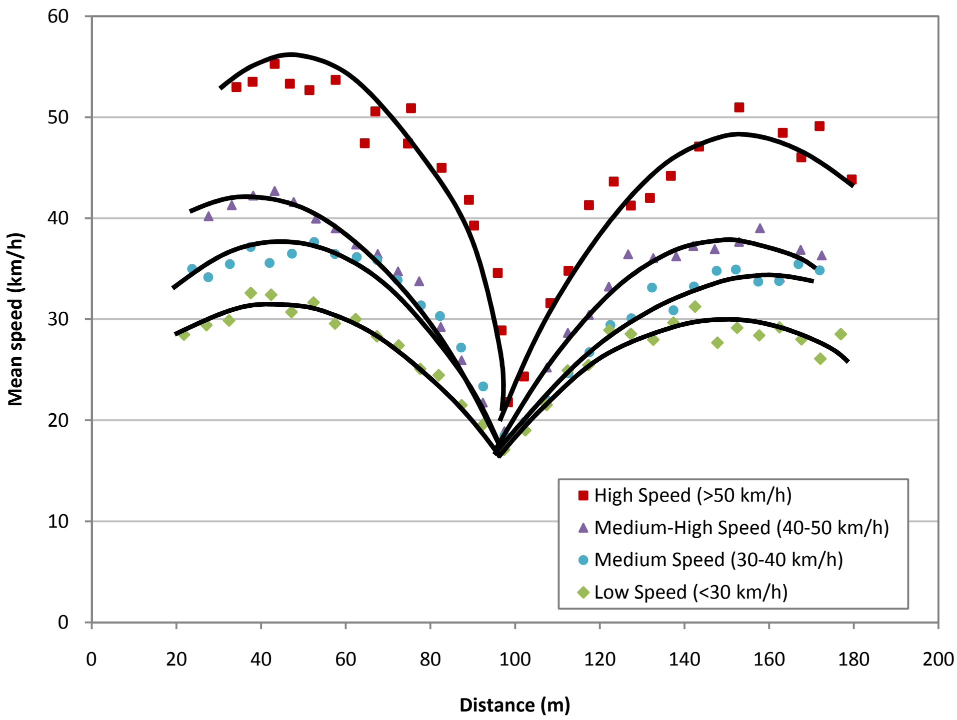


Figure 4.16 – Comparison of speed profiles of drivers grouped by initial travelling speed on a street with a speed hump

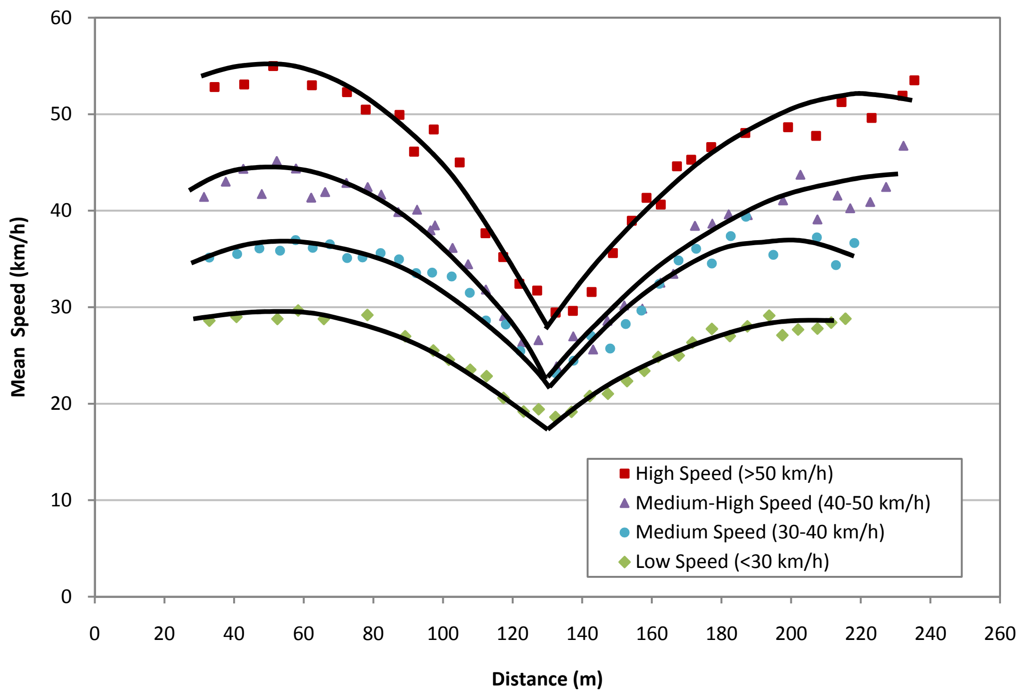


Figure 4.17 – Comparison of speed profiles of drivers grouped by initial travelling speed on a street with a raised one-lane angled slow point

This implies that drivers were more inclined to alter their speeds to lower levels on streets with devices that feature vertical deflection than those with narrowings. The speed alteration was also found to be more pronounced for faster drivers.

However, there was no significant change in speed levels observed for all driver groups when a narrowing was involved (see *Figure 4.18*).

In addition, drivers travelling at higher initial speeds negotiated the devices at higher device operating speeds compared to those with lower initial travelling speeds (see *Figures 4.16* to *4.18*).

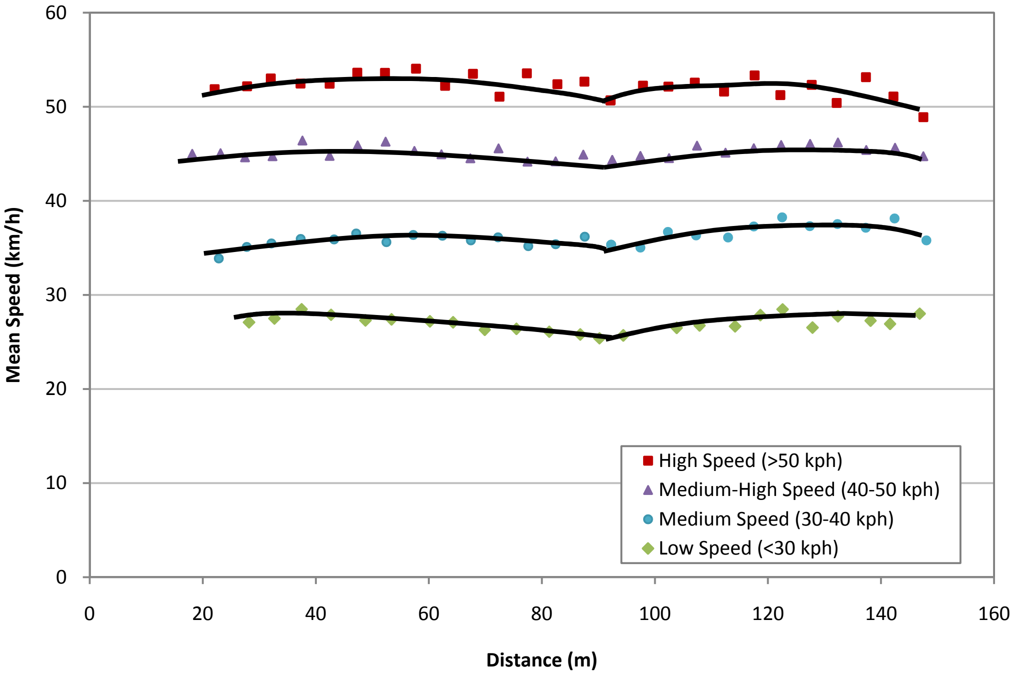


Figure 4.18 – Comparison of speed profiles of drivers grouped by initial travelling speed on a street with a flush two-lane narrowing

4.3 Speed change

The speed change, i.e. the drop from street speed to operating speed was used to represent the speed reducing effect of traffic calming devices. The highest 85th percentile speed observed along the street (mainly on sections not impeded by traffic calming device) was fixed as the street speed.

The speed change obtained for each device reflects the reduction in speed that may be achieved once motorists have reached the device after travelling from a distance not significantly influenced by the device. *Figure 4.19* shows the speed changes that were derived from the street speeds and device operating speeds of the devices covered in this study.

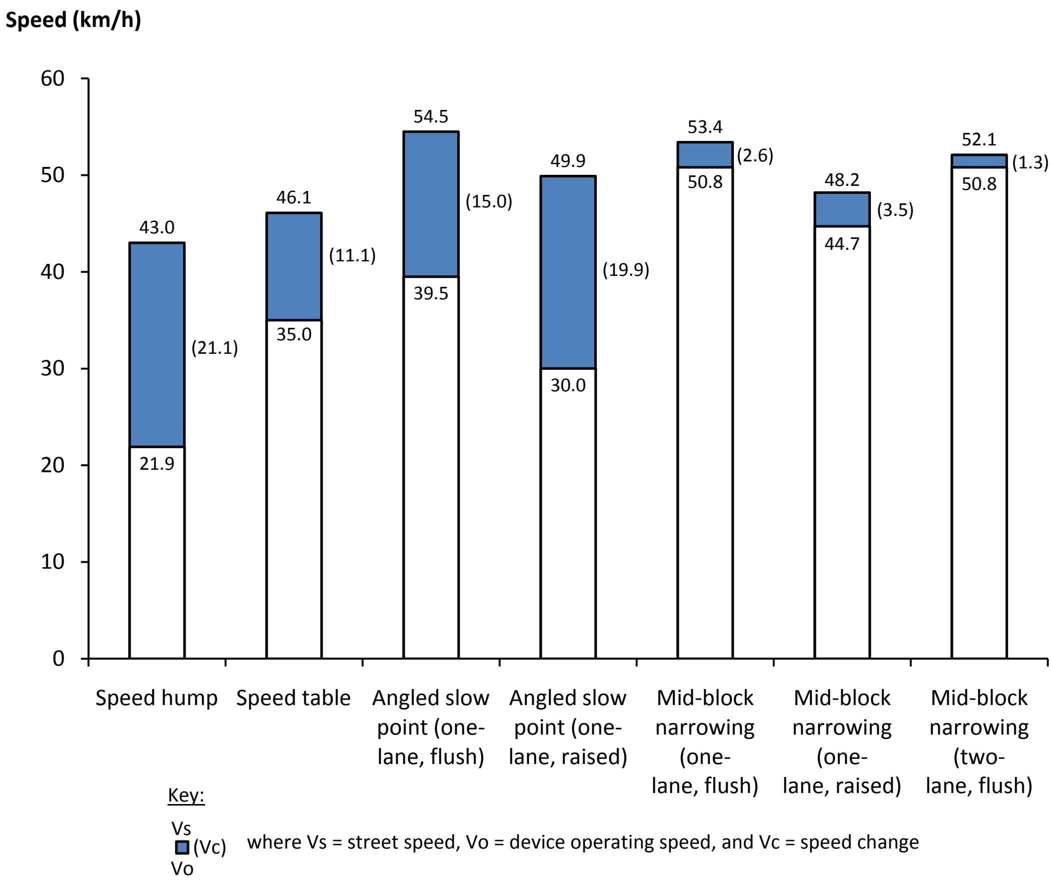


Figure 4.19 – Changes in 85th percentile speeds for single devices

Of the seven devices studied, the speed hump was most effective while the least effective device was the two-lane narrowing. Overall, narrowings performed poorly, with the changes in speed being small.

The raised one-lane angled slow point performed better than the speed table, in terms of lowering speeds from the unimpeded segment to the device. The element of vertical deflection in addition to the lateral deflection probably contributed greatly to the effectiveness of this device.

Vertical deflections appear to be more advantageous in maintaining speeds below 50 km/h throughout the entire length of a street. By contrast, for horizontal deflections, 85th percentile speeds on unimpeded segments were mostly in excess of 50 km/h. This may reflect the ability of drivers to align their approach to horizontal devices to minimise the speed reduction.

The change from highest mean street speed recorded at a distance from the device to the mean speed at the device is given in *Table 4.6*.

Table 4.6 – Changes in mean speeds

Device	Mean Speed at Device (km/h)	Highest Mean Street Speed (km/h)	Change in Mean Speed (km/h)	Significance of change in mean speed
Speed hump	17.6	36.6	19.0	Significant ($p \approx 0$)
Speed table	24.5	40.1	15.6	Significant ($p \approx 0$)
Angled slow point *One-lane, flush*	33.8	46.4	12.6	Significant ($p \approx 0$)
Angled slow point *One-lane, raised*	24.6	42.7	18.1	Significant ($p \approx 0$)
Narrowing *One-lane, flush*	44.2	46.0	1.8	Less significant ($p = 0.084$)
Narrowing *One-lane, raised*	34.4	41.1	6.7	Significant ($p \approx 0$)
Narrowing *Two-lane, flush*	43.5	44.9	1.4	Less significant ($p = 0.081$)

The changes in mean speed were much higher than the changes in 85th percentile speed for the speed table and the one-lane raised narrowing (refer to *Figure 4.8* for 85th percentile speed changes). This might be due to the devices having a larger influence on slow drivers than on fast drivers.

When tested for significance using the independent *t*-test at a 5% significance level ($\alpha = 0.05$), the speed reductions were significantly larger than zero for all the devices, except for the flush narrowings (one-lane and two-lane). The reductions in speed for the flush narrowings yielded *p*-values of about 0.08, which showed that the changes were less significant. The detailed test results are shown in *Appendix E*.

The speed changes obtained from this study serve as an estimate of the amount of speed reduction that may be achieved with respect to the type of device and the prevailing street speed. Thus, the speed changes for other streets with similar devices may not necessarily correspond with those obtained here. This is because street speed is, to a certain extent, a function of the available distance leading up to the device. This will be discussed further in the subsequent sections.

While it is believed that road width has a major influence on speed on conventional (non-calmed) local streets, its influence may somewhat be less dominant on calmed local streets. Regression analysis was conducted to test this hypothesis by attempting to relate street speed on traffic-calmed streets with actual and effective road width, the latter taking into account the impact of on-street parking.

Results show that the relationships between street speed and both actual and effective road width were weak ($R^2 = 0.206$ and $R^2 = 0.216$ respectively), although both models and their respective parameter coefficients were quite close to being significant, assuming a 95% level of confidence (see *Table 4.7*).

Table 4.7 – Output summary for analysis relating street speed with actual and effective widths

Model Summary (Street speed vs Actual width)
R-square: 0.206   Standard Error: 5.640
ANOVA
F-statistic: 3.895   Significance: 0.067
Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	63.713	8.799	7.241	0.000
Actual road width	-1.763	0.893	-1.973	0.067

Model Summary (Street speed vs Effective width)
R-square: 0.216   Standard Error: 5.603
ANOVA
F-statistic: 4.141   Significance: 0.060
Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	56.132	4.897	11.463	0.000
Actual road width	-1.501	0.738	-2.035	0.060

4.4 Zone of influence

The zone of influence is the area over which a traffic calming device produces a noticeable speed-reducing effect. For single devices, it may be assumed that the zone of influence per direction is consistent if the approach lengths are assumed equal; hence the total zone of influence is twice the directional zone of influence.

Angled slow points exerted the most extensive zones of influence (see *Figure 4.20*). Drivers began reducing their speeds at 100 – 110 m from the device. This was probably due to the appearance of the device, which from a distance resembles a mid-block closure.

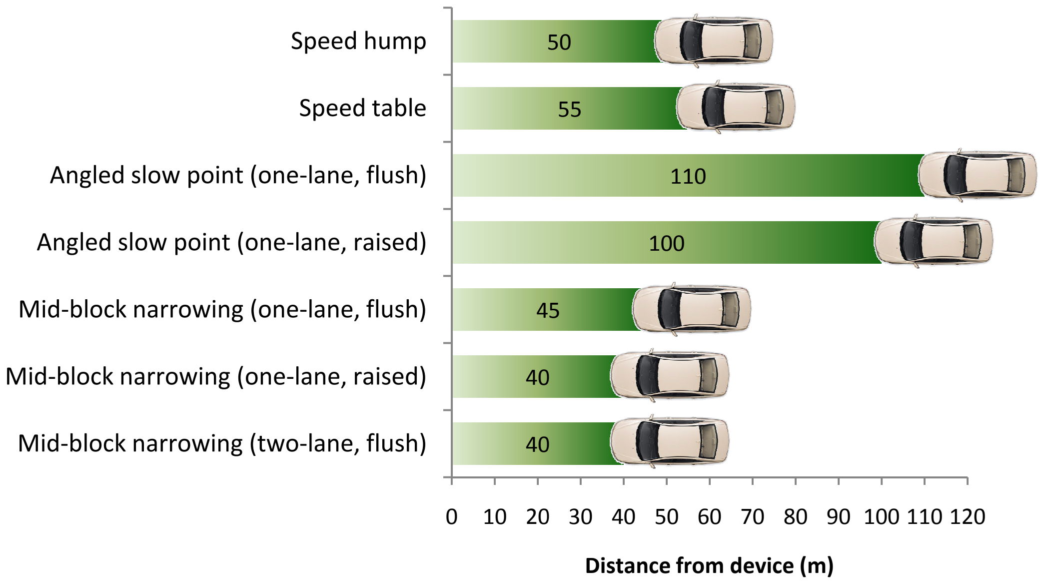


Figure 4.20 – Zone of influence (per direction) produced by single devices

Narrowings produced the smallest zones of influence as drivers began lowering the speed of their vehicles 40 – 45 m from the device. However, speed reductions were considerably smaller than those obtained for the other devices.

Drivers approaching vertical deflections started to reduce their speeds at 50 – 55 m from the device, which was particularly short for the speeds hump, given the sizeable speed reduction involved. It should be noted that the approach speed for the speed hump was quite low; therefore a higher approach speed would have produced a longer zone of influence.

Approach length has an effect on the approach speed, hence the zone of influence also. Longer approaches may produce higher approach speeds, and therefore longer zones because drivers need to start slowing down earlier in order to achieve desirable operating speeds. However, it should be noted that drivers may opt to drive at lower speeds even on longer approaches.

The relationships between zone of influence (Z) and approach speed (V_A), and approach length (L_A) for speed humps were best explained using the following linear equations:

$$Z = 2.882V_A - 76.716 \quad (4.1)$$

$$Z = 0.214L_A + 16.763 \quad (4.2)$$

Note that these models are valid only for isolated speed humps with approach lengths within the range of 30 – 200 m and approach speeds between 30 – 50 km/h.

The regression output is provided in *Table 4.8*, while the estimated curves are shown in *Figures 4.21* and *4.22*.

Table 4.8 – Output summary for device operating speed models

Model	R^2	*F*-statistic	Sig. *F*		Coefficients	*t*-statistic	Sig. *t*
1	0.553	22.280	0.000	V_A	2.882	4.720	0.000
				Constant	-76.716	-3.079	0.006
2	0.534	20.646	0.000	L_A	0.214	4.544	0.000
				Constant	16.763	2.935	0.009

Model 1 = Zone of influence versus Approach speed, Model 2 = Zone of influence versus Approach length, R^2 = coefficient of determination, Sig. *F* = significance value of the *F*-statistic, Sig. *t* = significance value of the *t*-statistic

An analysis was performed to relate approach length and approach speed. This is further discussed in Section 4.8.

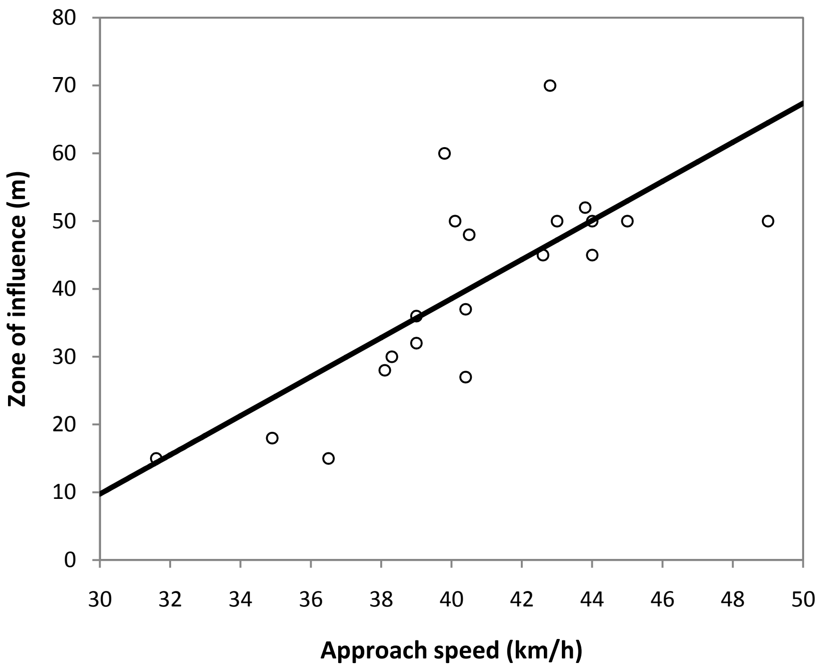


Figure 4.21 – Relationship between zone of influence and approach speed for speed humps

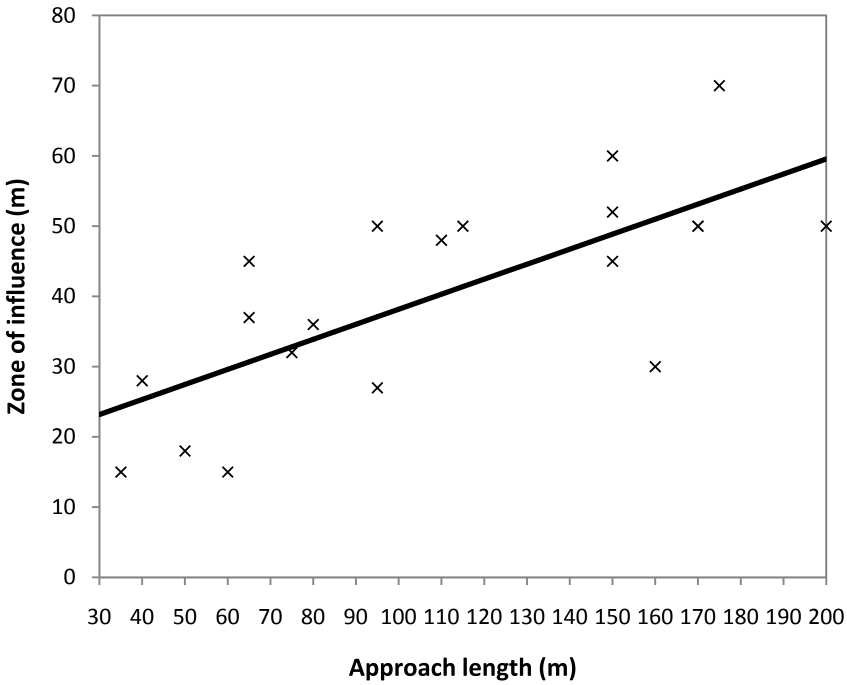


Figure 4.22 – Relationship between zone of influence and approach length for speed humps

4.5 Speed estimation using speed differential relationships

Speed differential is the difference between the speed at a distance from a traffic calming device and the device operating speed. The speed differentials were determined using the operating speeds established in Section 4.1 and data from the speed profiles for single devices (refer to Sections 4.2.1).

Plots of speed differential against distance showed that 85th percentile speeds within the influence zones of streets calmed by single devices can be estimated using quadratic functions, with the exception of the one-lane flush narrowing, which was better explained by a linear function than a quadratic one.

Figure 4.23 illustrates the 85th percentile speed differential between a point within the influence zone and at the device. The curves provide a means of estimating speed differentials as far as the start of the influence zone.

The standard errors of the estimate for the curves were between 0.03 – 0.22, which reflected the high accuracy of the models. The significance of the F-statistic and t-statistic values were much smaller than 0.05, which showed that the coefficients were significantly different from zero, thus the models were good enough to predict the speed differences. *Table 4.9* summarises the regression outputs of the models.

Table 4.9 – Regression outputs for the speed differential relationships

Device	SEE	*F*-statistic	Sig. *F*		Coefficients	*t*-statistic	Sig. *t*
Speed hump	0.03	753037.4	0.000	x	0.8215	491.4	0.000
				x^2	-0.0080	-201.5	0.000
Speed table	0.13	13600.3	0.000	x	0.3533	57.6	0.000
				x^2	-0.0027	-21.1	0.000
Angled slow point *One-lane, flush*	0.07	133768.3	0.000	x	0.2552	200.8	0.000
				x^2	-0.0011	-75.8	0.000
Angled slow point *One-lane, raised*	0.08	196554.3	0.000	x	0.3979	252.9	0.000
				x^2	-0.0020	-102.4	0.000
Narrowing *One-lane, flush*	0.21	418.7	0.000	x	0.0611	20.5	0.000
Narrowing *One-lane, raised*	0.07	3702.6	0.000	x	0.1978	38.1	0.000
				x^2	-0.0028	-18.4	0.000
Narrowing *Two-lane, flush*	0.04	1338.4	0.001	x	0.0629	20.6	0.000
				x^2	-0.0008	-8.5	0.003

SEE = standard error of the estimate, Sig. *F* = significance value of the *F*-statistic, Sig. *t* = significance value of the *t*-statistic

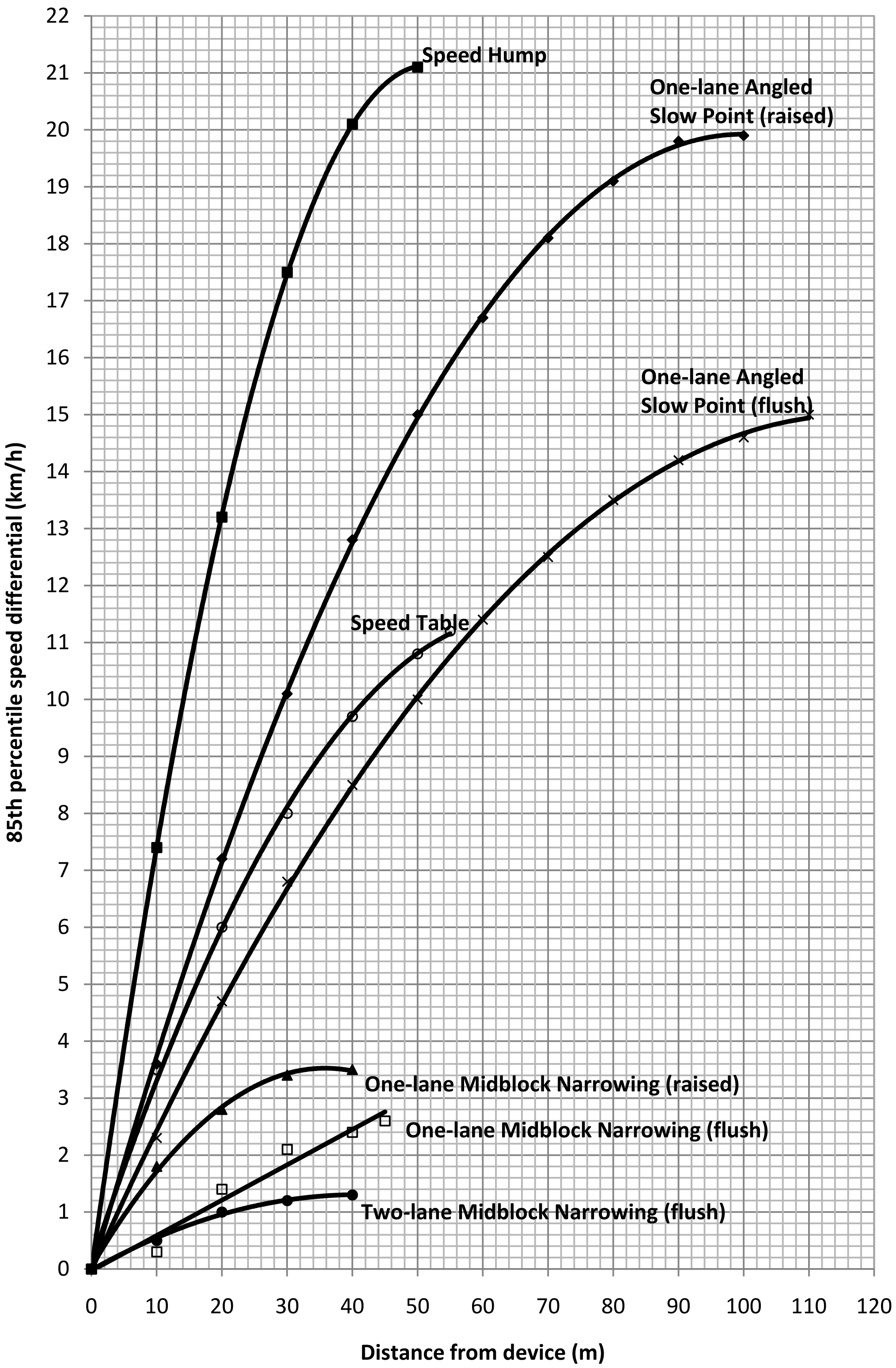


Figure 4.23 – Speed differential curves for single devices

4.6 Variation of speeds at traffic calming devices

For the seven case studies, the standard deviation in speeds recorded at impeded and unimpeded sections on the streets were all below 10 km/h, except for the street with a raised narrowing, where a standard deviation of 11.5 km/h was recorded at the device.

From standard deviation plots, it was noticeable that deviations at the speed table and the raised narrowing were higher than on unimpeded sections, thus indicating a distinctively varied choice of crossing speed. All other devices showed standard deviations approximately the same or lower than standard deviations on the unimpeded sections (refer to *Figures 4.1* to *4.7* in Section 4.2.1).

The speed data were first tested for normality. The frequency histograms indicated that the data were roughly normally distributed, while the normal Q-Q plots suggested that the data in the centre of the distributions were very close to normal. However, departures from normality, mostly slight, were present at the tails of the distributions.

The K-S statistics were less than the critical values, demonstrating the closeness of the data in the central region to normal. The further the departures from normality were, the larger the K-S and A-D statistics got. This was particularly apparent in the A-D tests, which reflected the effect of departures from normality at the tails of the distributions on the test statistics (see *Appendix F*).

Some of the K-S and A-D tests resulted in the rejection of the null hypothesis, which meant that the data did not closely follow a normal distribution. These results were anticipated as both the K-S and A-D tests are more sensitive to slight departures from normality.

The normal Q-Q plots provided a more reasonable verdict for the normality checks. The K-S and A-D tests were used as auxiliary tools in assessing the degree of seriousness of departures from normality. Therefore, as the normal Q-Q plots showed no extreme departures from normality, there is reason to believe that the distributions of the speeds are approximately normally distributed.

To obtain statistical significance for the variation of speed between impeded and unimpeded sections, *F*-tests for the equality (or inequality) of variances were employed. A summary of the test results are provided in *Table 4.10*. The statistical outputs of the tests are provided in *Appendix G*.

It should be noted that Bartlett's test and Levene's test were also used to test the equality of variances. However, results from both tests were mostly inconsistent with the F-test results and each other. The F-test results were accepted, given the finding that the speeds were close to being Normally distributed.

Table 4.10 – Results for equality of variances in speeds for single devices

	Comparison of variance on unimpeded segments with respect to variance at devices									
Distance to device (m)	**100**	**90**	**80**	**70**	**60**	**50**	**40**	**30**	**20**	**10**
Speed hump						+	+	+	+	+
Speed table						–	–	–	–	=
Angled slow point (One-lane, flush)	+	=	=	=	+	+	+	=	=	=
Angled slow point (One-lane, raised)	+	+	+	+	+	+	+	+	+	+
Narrowing (One-lane, flush)						=	=	=	=	=
Narrowing (One-lane, raised)						–	–	–	–	=
Narrowing (Two-lane, flush)						=	=	=	=	=
Distance from device (m)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**
Speed hump	+	+	+	+	+					
Speed table	=	–	–	–	–					
Angled slow point (One-lane, flush)	=	=	=	=	=	+	=	=	=	=
Angled slow point (One-lane, raised)	+	+	+	+	+	+	+	+	+	+
Narrowing (One-lane, flush)	=	=	=	=	=					
Narrowing (One-lane, raised)	=	–	–	–	–					
Narrowing (Two-lane, flush)	=	=	=	=	=					

Key: +/–/= denotes significantly larger/smaller/equal variance in speed, compared to variance in speed at the device

It was found that the variance in speed at the speed hump was significantly lower than the variances on unimpeded sections. For one-lane angled slow points, the results were contrasting. The raised angled slow point had an effect similar to the speed hump. The flush variant, however, did not yield any significant differences in speed variance in 15 out of 20 street segments tested.

Interestingly, the speed table and the raised one-lane narrowing had the opposite effect. Variances in speed at distances 20 m or more from these two devices were significantly smaller than the variance at the device. The flush narrowings had very similar variances in speed at the devices and on unimpeded segments.

4.7 Influence of hump width on device operating speed

The relationship between the device operating speed of a speed hump (V_o) and the hump width to road width ratio (W_H/W_R) showed statistical significance using both S-curve and Power functions.

However, the S-curve model demonstrated a slightly higher statistical significance than the Power model. In addition, the shape of the S-curve model explained the relationship more appropriately, particularly for smaller ratios where speeds were expected to fall sharply as narrower speed humps were used. Therefore the following S-curve model was selected to represent the relationship:

$$V_o = \exp\left(3.474 - \frac{0.113}{W_H / W_R}\right) \tag{4.3}$$

Table 4.11 provides the regression output, while *Figure 4.24* shows the observed and predicted values of V_o obtained for both S-curve and Power models.

Table 4.11 – Output summary for device operating speed models

Model	SEE	*F*-statistic	Sig. *F*		Coefficients	*t*-statistic	Sig. *T*
S-curve	0.114	7.148	0.011	W_H/W_R	-0.113	-2.674	0.011
				Constant	3.474	54.063	0.000
Power	0.115	6.240	0.016	W_H/W_R	0.162	2.498	0.016
				Constant	28.916	35.118	0.000

SEE = standard error of the estimate, Sig. *F* = significance value of the *F*-statistic, Sig. *t* = significance value of the *t*-statistic

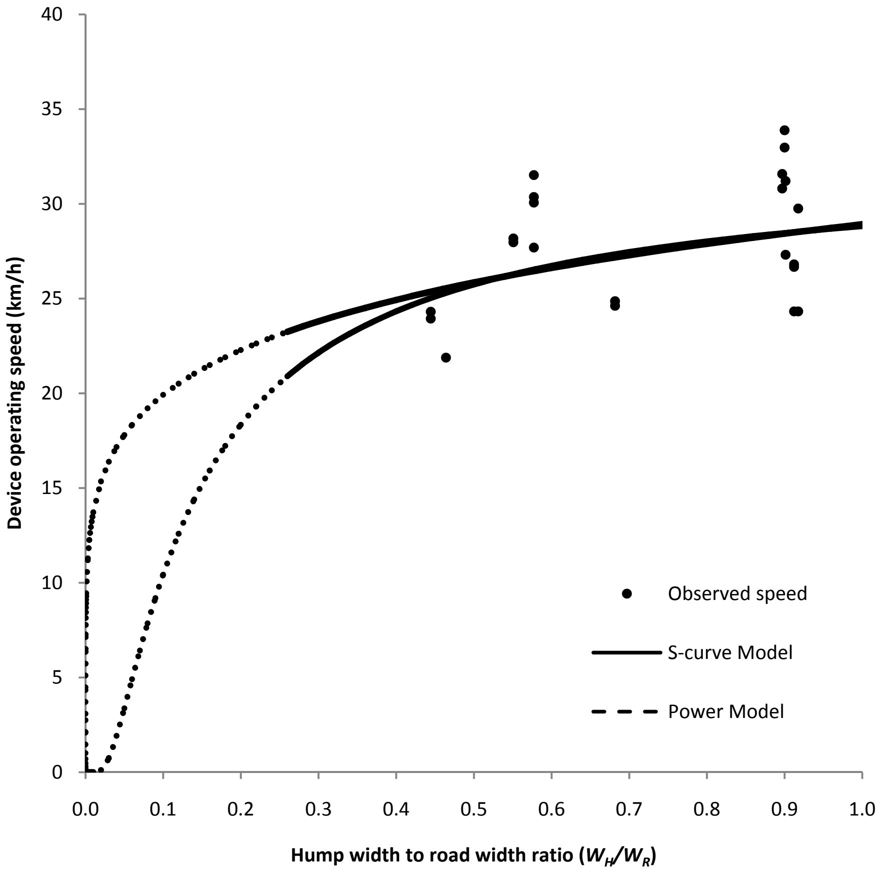


Figure 4.24 – Fitted curves for device operating speed models

It was found that the width of a speed hump with respect to the roadway width had an effect on device operating speed. Smaller W_H/W_R ratios produced lower speeds, as illustrated by the speed reduction curves in *Figure 4.25*.

Evidently, drivers are influenced by the narrowing of speed humps. This influence is more noticeable on wider streets, where the use of a speed hump partially constructed across the street causes drivers to perceive that their travel path is not only vertically deflected but also significantly constricted.

On the other hand, if a speed hump of similar dimensions was to be placed on a narrower street, the impact it would have on drivers would be smaller, as demonstrated by the estimated speed curves in *Figure 4.26*.

Also, the model suggests that a 12 m wide street with a 6 m wide speed hump will produce an operating speed approximately 10% lower than a speed hump constructed fully across the street, i.e. a 11 m wide hump (refer to *Figure 4.25*).

However, an 8 m wide street with a 6 m wide speed hump will produce an operating speed approximately 2% lower than a speed hump constructed fully across the street (7 m wide hump).

The smaller change in speed predicted on the narrower street can be explained by the lower travel speeds the street naturally produces. Therefore, it may be more cost-effective to combine a speed hump and narrowing on wider streets (≥ 10 m) than on narrower streets (≤ 9 m).

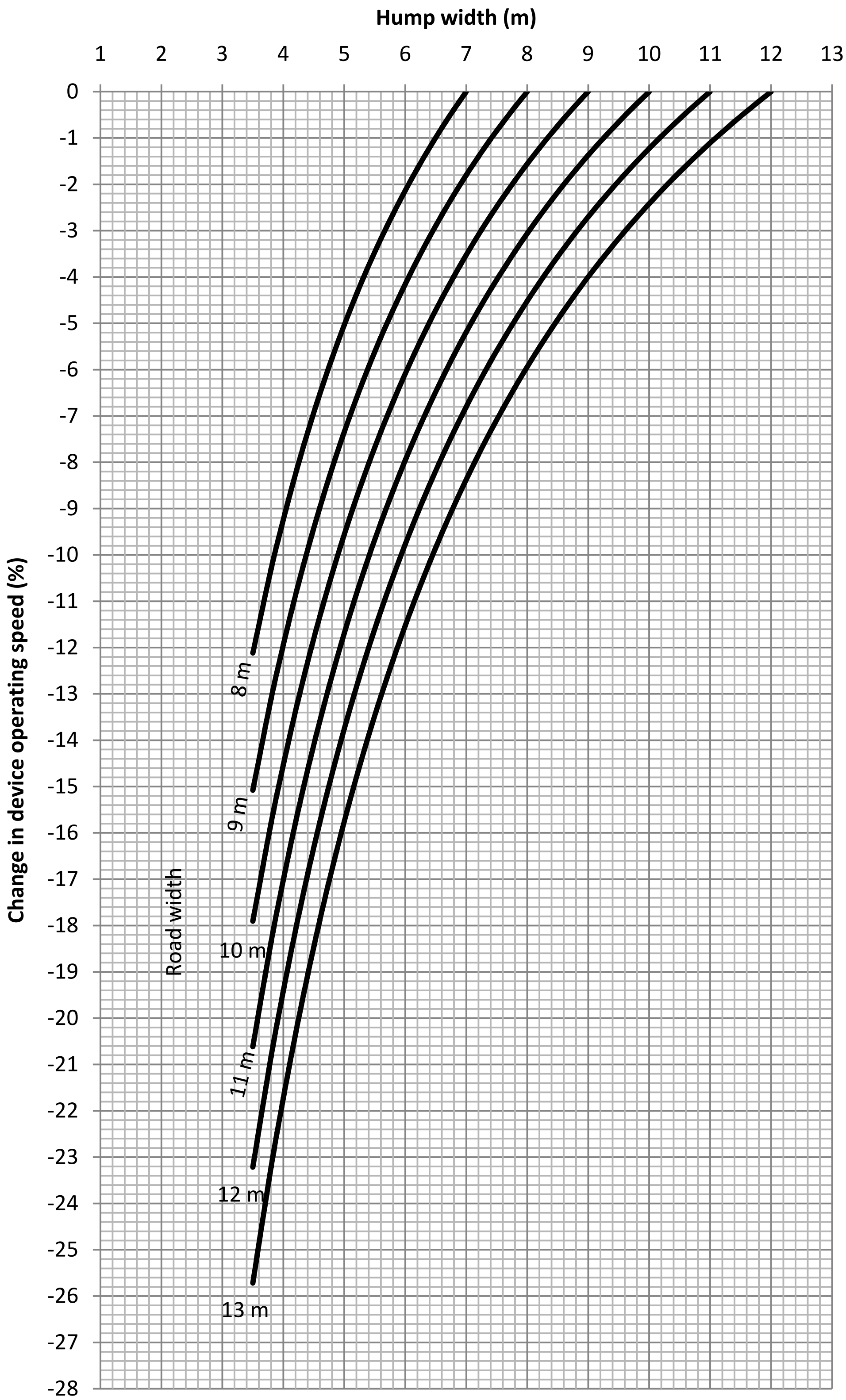


Figure 4.25 – Change in device operating speed with respect to speed on hump constructed fully across a street

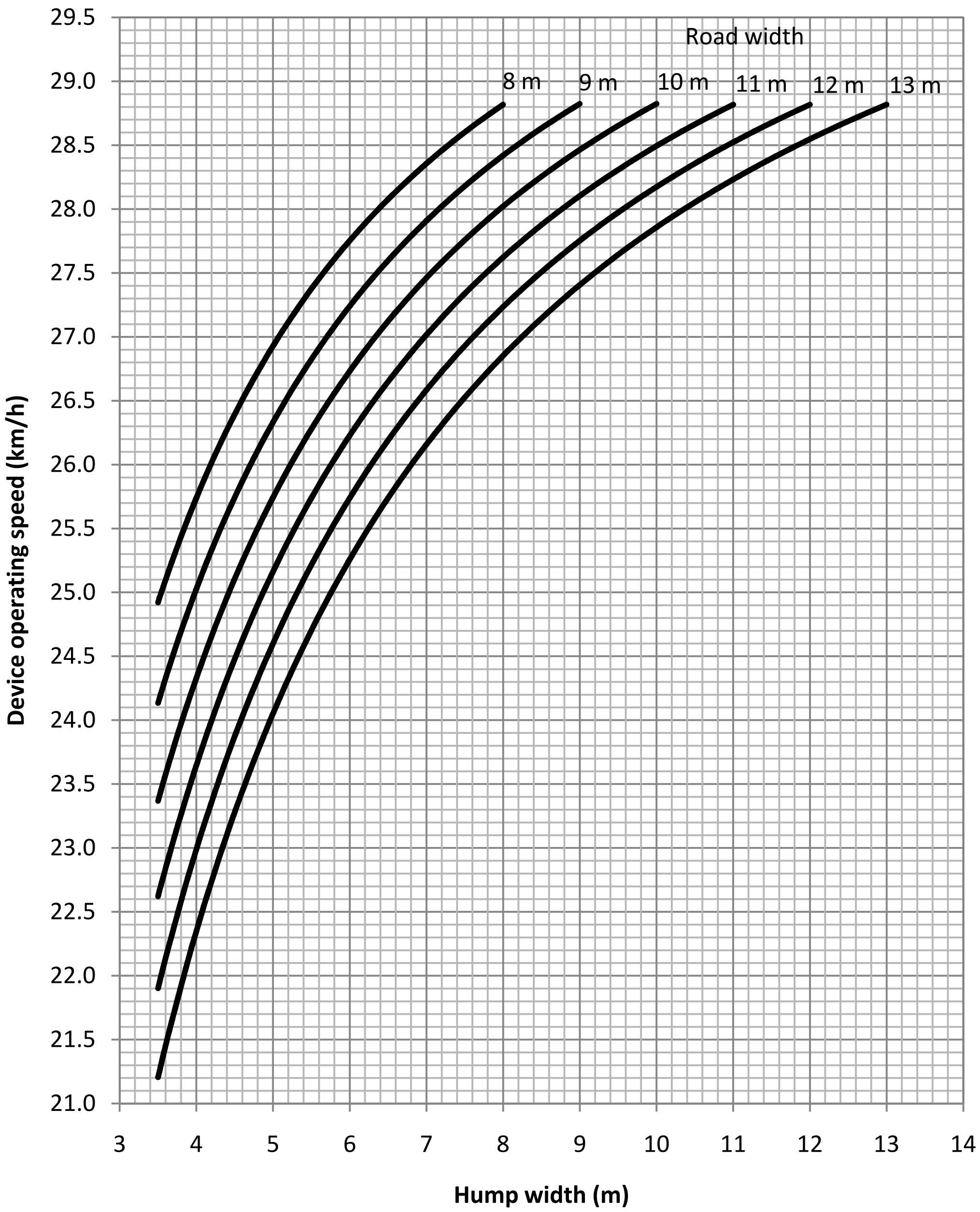


Figure 4.26 – Estimated device operating speeds based on hump and road widths

4.8 Speed prediction models: Approach speeds

The S-curve model was found to best represent the relationship between the speed differential (ΔV_A) and approach length (L_A) as it does not imply that speeds increase ad infinitum as the approach length increases, and it allows for the fitting of a value at zero approach length.

Substituting the speed differential models and device operating speed (V_o) into equation 3.9 yielded the following models for estimating the 85th percentile speed on the approach to a speed hump ($V_{AE(85)}$) and the mean speed on the approach to a speed hump, ($V_{AE(mean)}$):

$$V_{AE(85)} = 29.1 + \exp\left(23.037 - \frac{53.676}{L_A}\right) \tag{4.4}$$

$$V_{AE(mean)} = 22.3 + \exp\left(2.979 - \frac{40.926}{L_A}\right) \tag{4.5}$$

The regression models and their coefficients were tested for significance using the *F*-statistic and *t*-statistic tests, respectively. The level of confidence was set as 95% (α = 0.05). The models and coefficients were statistically significant, as indicated by significance values less than 0.05.

A summary of the regression analysis is given in *Table 4.12*, while the estimated speed curves with reference to the observed values are shown in *Figure 4.27*. The complete results for the S-curve model, along with other models tested (Power, Logarithmic and Linear), can be found in *Appendix H*.

Table 4.12 – Output summary for speed differential on the approach

Model Summary (85th Percentile Speed)

R-square: 0.620   Standard Error: 0.209

ANOVA

F-statistic: 22.814   Significance: 0.000

Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	3.037	0.125	24.303	0.000
Approach length	-53.676	11.238	-4.776	0.000

Model Summary (Mean Speed)

R-square: 0.476   Standard Error: 0.312

ANOVA

F-statistic: 14.556   Significance: 0.002

Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	2.979	0.148	20.149	0.000
Approach length	-40.926	10.727	-3.815	0.002

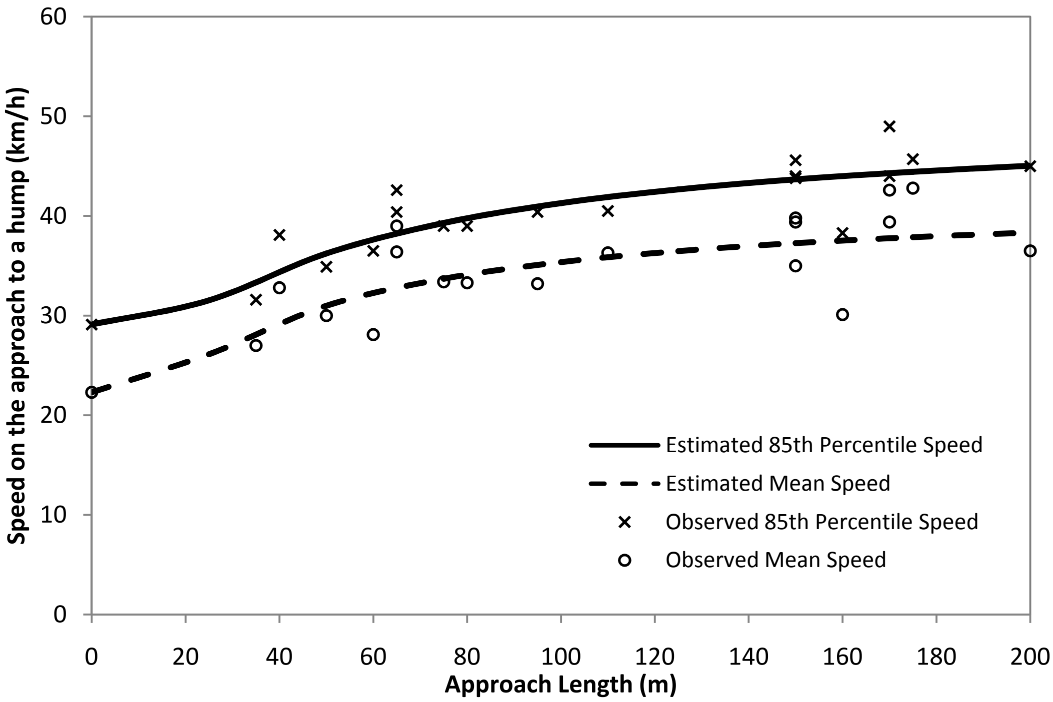


Figure 4.27 – Estimated speed curves using the approach speed models

The model suggests that placing a hump 40 – 85 m from a street entry or a small-radius curve should ensure 85th percentile speeds between 35 – 40 km/h on the approach to the first hump in a series.

Attempts to obtain similar prediction models for speed tables were unsuccessful (refer to *Appendix H*), as the *F*-statistics were very low, thus implying that the models did not explain much of the variation in the data. In addition, results from the *t*-statistic tests suggested that the coefficients were not significantly different from zero. This was due to the limited range in speeds and approach lengths in the empirical data.

4.9 Speed prediction models: Inter-device speeds

The 85th percentile and mean speed differentials between devices were associated with the device spacing (L_S) using S-curve models, which again exhibited better correlation than the other models tested.

The S-curve models suggest that smaller increases in speed are expected at larger spacings and the speed for zero spacing is effectively the device operating speed. These models were thought to represent the speed-spacing relationship more sensibly than linear models, which imply that speed increases ad infinitum as spacing increases.

By substituting the speed differential models (ΔV_S) and the device operating speed (V_o) into equation 3.10, the following models were obtained for estimating the 85th percentile speed between devices ($V_{SE(85)}$) and mean speed between devices ($V_{SE(mean)}$):

For speed humps,

$$V_{SE(85)} = 29.1 + \exp\left(3.427 - \frac{86.777}{L_S}\right) \tag{4.6}$$

$$\mathrm{V}_{\mathrm{SE(mean)}} = 22.3 + \exp\left(3.266 - \frac{61.609}{\mathrm{L_S}}\right) \tag{4.7}$$

For speed tables,

$$V_{SE(85)} = 37.2 + \exp\left(3.313 - \frac{133.964}{L_S}\right) \tag{4.8}$$

$$V_{SE(mean)} = 27.2 + \exp\left(3.157 - \frac{66.778}{L_S}\right) \tag{4.9}$$

Tables 4.13 and *4.15* provide summaries of the regression output for speed humps and speed tables, respectively. The complete results of the regression analysis for all functions tested can be found in *Appendix I*.

Figure 4.28 shows the estimated 85th percentile and mean speed between speed humps, compared with each other, and with the observed values.

Table 4.13 – Output summary for speed differential between speed humps

Model Summary (85th Percentile Speed)
R-square: 0.978 Standard Error: 0.126
ANOVA
F-statistic: 446.900 Significance: 0.000
Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	3.427	0.055	62.170	0.000
Spacing	-86.777	4.105	-21.140	0.000

Model Summary (Mean Speed)
R-square: 0.940 Standard Error: 0.151
ANOVA
F-statistic: 157.934 Significance: 0.000
Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	3.266	0.066	49.605	0.000
Spacing	-61.609	4.902	-12.567	0.000

Table 4.14 – Output summary for speed differential between speed tables

Model Summary (85th Percentile Speed)				
R-square: 0.680	Standard Error: 0.380			
ANOVA				
F-statistic: 21.222	Significance: 0.001			
Coefficients				
	Coefficient	Standard Error	t-statistic	Significance
Constant	3.313	0.226	14.671	0.000
Spacing	-133.964	29.080	-4.607	0.001
Model Summary (Mean Speed)				
R-square: 0.654	Standard Error: 0.201			
ANOVA				
F-statistic: 18.898	Significance: 0.001			
Coefficients				
	Coefficient	Standard Error	t-statistic	Significance
Constant	3.157	0.119	26.462	0.000
Spacing	-66.778	15.361	-4.347	0.001

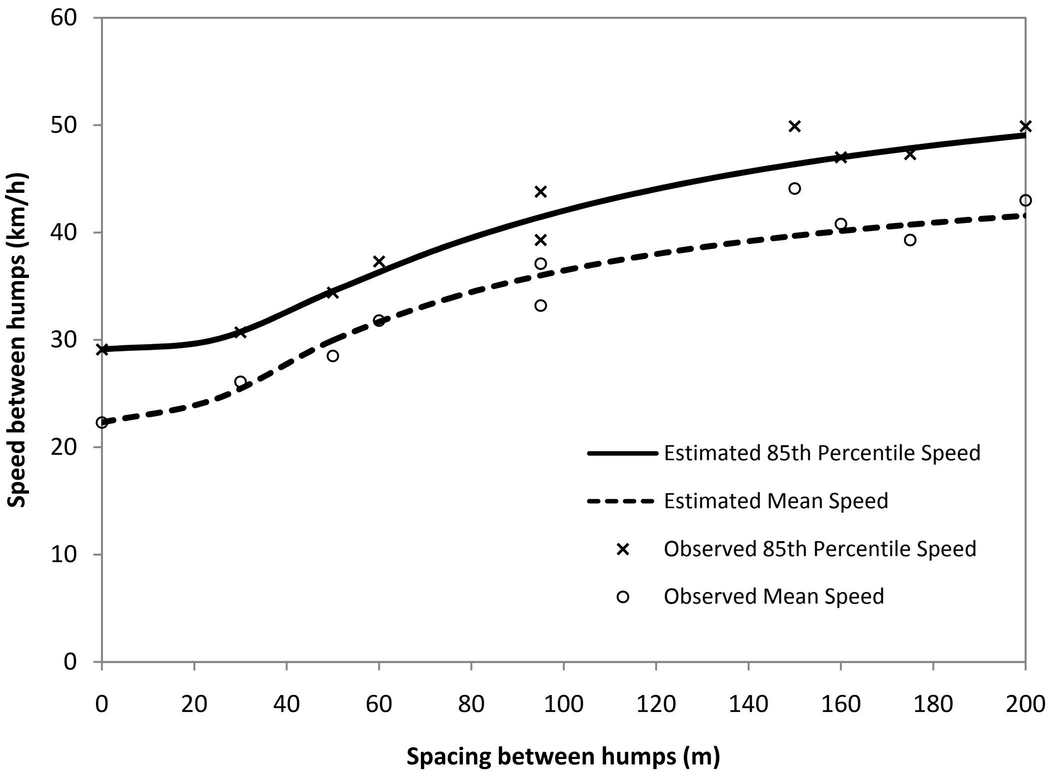


Figure 4.28 – Speed-spacing models for speed humps

The models suggest that 85th percentile speeds can be maintained between 35 and 40 km/h and between 40 and 45 km/h if humps are spaced 50 – 80 m and 80 – 130 m apart, respectively, while mean speeds of 30 – 40 km/h are achievable for spacings 50 – 155 m.

Comparisons of the estimated 85th percentile and mean speed between speed tables, and the observed values are shown in *Figure 4.29*.

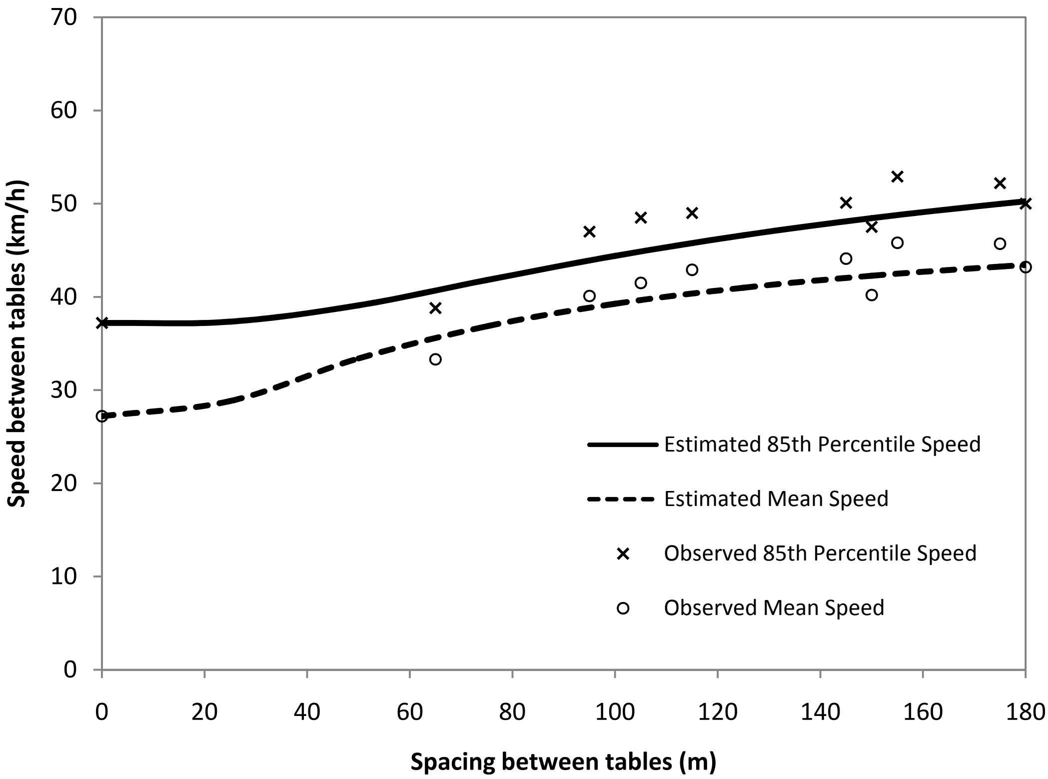


Figure 4.29 – Speed-spacing models for speed tables

It is recommended that speed tables be spaced at 55 – 105 m in order for 85th percentile speeds to be within the 40 – 45 km/h range, while placing speed tables 60 – 110 m apart should result in mean speeds between 35 and 40 km/h.

Table 4.15 provides a summary of recommended spacings for speed humps and speed tables based on the prediction curves shown in *Figures 4.30* and *4.31*.

Table 4.15 – Recommended spacings for speed humps and speed tables

Device	Spacing (m) required to achieve inter-device speed						
	85th percentile speed (km/h)				Mean speed (km/h)		
	35	40	45	50	30	35	40
Speed humps	≤ 50	≤ 80	≤ 130	≤ 220	≤ 50	≤ 85	≤ 155
Speed tables	*	≤ 55	≤ 105	≤ 175	≤ 30	≤ 60	≤ 110

* Speed not attainable

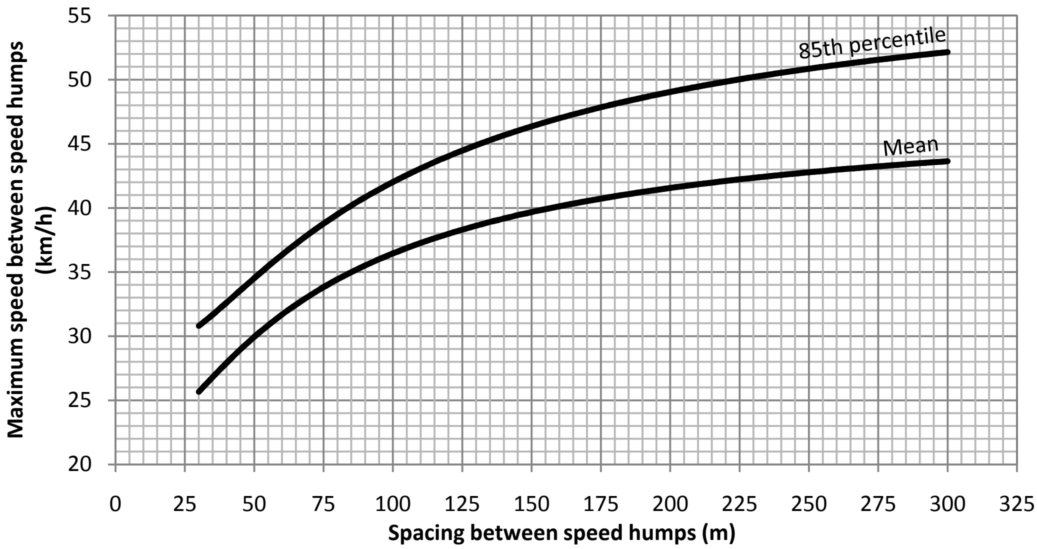


Figure 4.30 – Estimated maximum speed between two successive speed humps

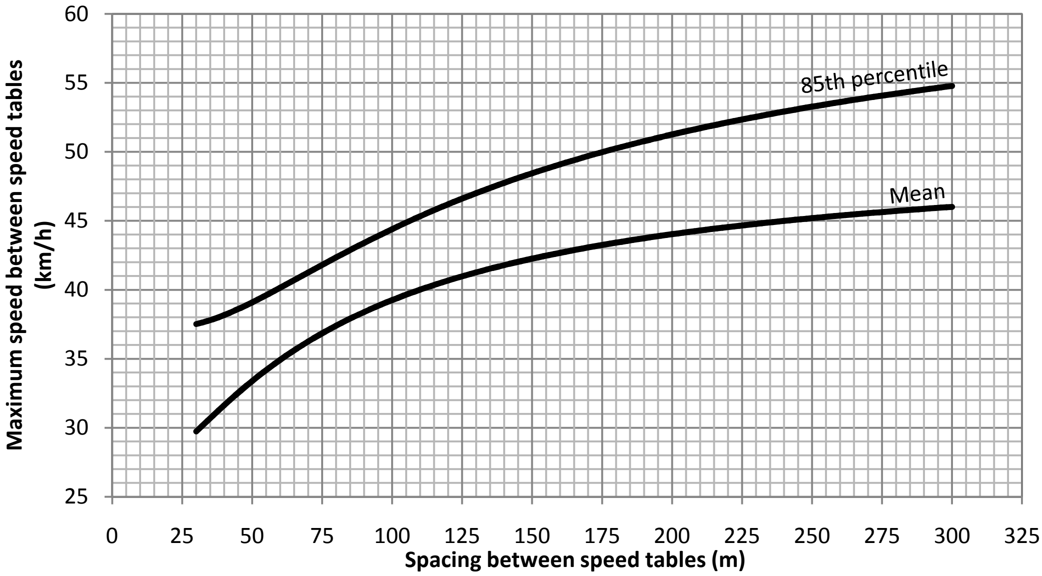


Figure 4.31 – Estimated maximum speed between two successive speed tables

4.10 Safety impact of traffic calming

The study of 28 traffic-calmed streets around Christchurch showed a 4.2% drop in total crashes/year/street, with 11 streets experiencing reductions of 0.17 – 0.67 crashes/year, and eight streets registering increases of 0.25 – 0.67 crashes/year. Crashes on four streets remained unchanged, while the other five did not record any crashes during the analysis periods (see *Table 4.16*).

Table 4.16 – Total crashes at the surveyed streets before and after implementation of traffic calming

No.	Street	Total crashes		Period	Total Crashes/year	
		Before	After	(years)	Before	After
1	Aylesford Street	6	5	3	2.00	1.67
2	Francis Avenue	1	3	3	0.33	1.00
3	Stratford Street	4	2	6	0.67	0.33
4	Snowdon Road	1	1	5	0.20	0.20
5	Hamilton Avenue	3	3	3	1.00	1.00
6	Burke Street	0	2	3	0.00	0.67
7	Rattray Street	0	0	2	0.00	0.00
8	Kirkwood Avenue	4	3	3	1.33	1.00
9	Randolph Street	2	3	3	0.67	1.00
10	Mackenzie Avenue	4	3	2	2.00	1.50
11	Perry Street	0	0	3	0.00	0.00
12	Barbour Street*	0	0	3	0.00	0.00
13	Grafton Street*	2	1	2	1.00	0.50
14	Grenville Street*	1	2	4	0.25	0.50
15	Baretta Street	1	1	4	0.25	0.25
16	Carrick Street	0	0	3	0.00	0.00
17	Flockton Street	1	3	3	0.33	1.00
18	Fairfield Avenue	3	3	3	1.00	1.00
19	Wherstead Road	0	0	6	0.00	0.00
20	Webb Street	1	0	6	0.17	0.00
21	Geraldine Street	5	4	6	0.83	0.67
22	Saltaire Street	3	2	4	0.75	0.50
23	Merivale Lane	4	6	7	0.57	0.86
24	Mary Street	10	6	6	1.67	1.00
25	Grants Road	9	5	6	1.50	0.83
26	Glenroy Street	3	1	3	1.00	0.33
27	Hastings Street	10	13	5	2.00	2.60
28	Wildberry Street	1	4	5	0.20	0.80
		79	76	112		
	Crashes/year/street	0.71	0.68			

* A speed limit of 40 km/h was introduced in conjunction with traffic calming for this street

Table 4.17 provides a summary of the crash rates observed at mid-block and intersections before and after traffic calming. The crash numbers are provided in *Appendix J*.

Crash rates at intersections were generally higher than those at mid-block. This was expected, given the higher number and more diverse types of traffic conflicts that can give rise to crashes at intersections. However, the number of intersection crashes/year/street dropped from 0.55 to 0.49 (-10.9%) after traffic calming initiatives were implemented. On the other hand, mid-block crashes/year/street rose from 0.15 to 0.19 (+26.7%).

Table 4.17 – Number of intersection and mid-block crashes at the surveyed streets before and after implementation of traffic calming

Crash type	No. of crashes		Period (years)	Crashes/year/street	
	Before	After		Before	After
Intersection crashes	62	55		0.55	0.49
Street-end crashes	41	29	112	0.37	0.26
Side road crashes	21	26		0.19	0.23
Mid-block crashes	17	21	112	0.15	0.19

As anticipated, there were more street-end crashes than side road crashes. However, there was a noticeable drop in street-end crashes/year/street from 0.37 to 0.26 (-29.7%) after the implementation of traffic calming. In contrast, side road crashes/year/street increased from 0.19 to 0.23 (+21.1%).

The increases in mid-block and side road crash rates are somewhat perplexing. Theoretically, one would expect reductions in crash rates along streets that have been traffic-calmed, as speed levels were likely to be reduced and drivers would, in some way, be more cautious and attentive while driving through these streets. This serves to show that crashes are random, unpredictable events that are more likely to be associated with human factors, and to a lesser extent, road and vehicle factors.

In order to justify the greater influence the driver may have in crash involvement over road and vehicle factors, the factors cited in all crashes were analysed.

Out of the 15 specified factors commonly cited in the crash reports, 12 were human factors, ranging from driving under the influence of alcohol to incompetent driving due to old age, disability or illness. The other three factors were weather, and unspecified road and vehicle factors. It is most likely that 'vehicle factor' refers to faulty vehicle conditions, while 'road factor' may include substandard pavement or roadway conditions. Not to be discounted is the possibility of roadway fixtures, such as traffic calming devices, being the cause of a crash.

Figure 4.32 shows the likelihood of crash factors being cited in a crash on a street before and after traffic calming measures were initiated. The derivation of these values is given in *Appendix K*.

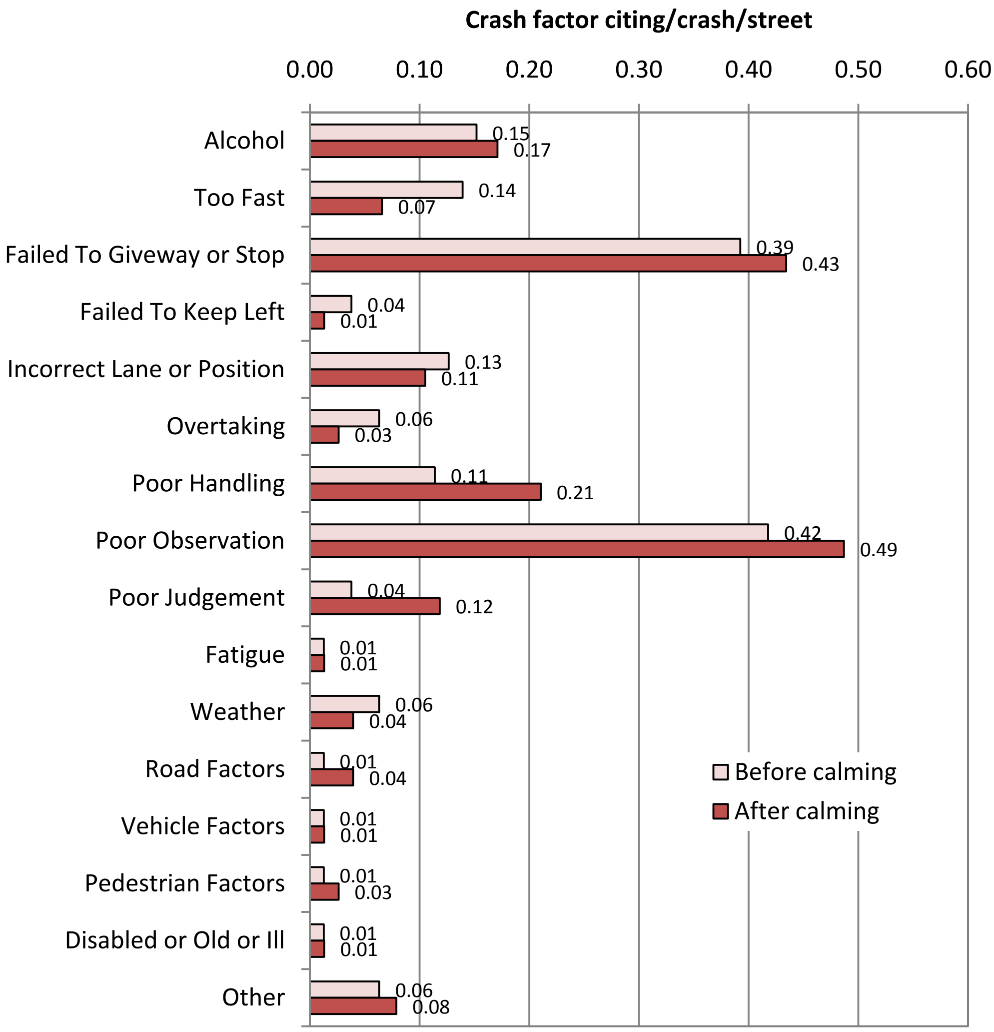


Figure 4.32 – Likelihood of crash factors being cited in a crash on a street

It was found that human factors were predominant in most crashes, with poor observation and failure to give way or stop being the two most prevalent factors. Other prevalent factors were driving under the influence of alcohol, incorrect lane position, poor handling and driving too fast.

It is important to note that the number of crashes due to speeding had dropped by 50% after traffic calming. This may be attributed mainly to the success of the traffic calming devices in bringing down speed levels.

Interestingly, there were increases in the number of crashes attributed to poor handling, poor observation and poor judgement, and for road factors after traffic calming measures were implemented. An initial reaction to this was to question if the traffic calming devices had anything to do with these increases.

Examining the crash reports revealed that there were only four cases in which crashes were connected to, or occurred at traffic calming devices. However, none of these cases involved contact with the devices.

A crash on Mackenzie Avenue involved a driver speeding through the angled slow point, losing control and crashing his car into a fence and a tree not far from the angled slow point. A similar crash took place on Aylesford Street, where a driver had crashed his vehicle after negotiating the speed table at high speed.

Another crash occurred at the two-lane narrowing on Stratford Street, where a recycling truck pulled out from the kerb and struck a car that was overtaking it.

A fourth crash took place at a T-intersection with kerb extensions on Geraldine Street, where a car came into contact with a cyclist. Although there is some concern about kerb extensions causing issues pertaining to encroachment of travel paths, drivers should anticipate the possibility of such a scenario taking place at narrowed roadway sections and allow cyclists to pass ahead of them. In this specific case, it was the driver who was at fault due to lack of consideration.

Therefore, it can be concluded that the rise in the frequency of the aforementioned crash factors was not due in large part to the implementation of traffic calming measures, as there is no strong evidence to show that the devices had directly caused the crashes.

Nevertheless, it should be acknowledged that to some extent, the presence of physical devices on streets may have some influence on safety, as certain drivers who may find negotiating these devices rather tricky. Conversely, some drivers might enjoy the challenge of negotiating traffic calming devices at higher speeds than the design speed. This, of course, does not bode well for their safety and the safety of other road users.

One of the major implications of road crashes is physical injury, which can be split into three levels of severity – minor, serious and fatal. Consequently, a study on the human cost of crashes was conducted using crash data from the 28 streets previously surveyed to see if there were any positive changes in crash severity after traffic calming measures were implemented, seeing as there were fewer speed-related crashes reported, and that speeds would generally be lower.

It was found that about 30% of the crashes had resulted in injuries, but none were fatal (refer to *Tables 4.18* and *4.19*). There was also a 9.5% drop in the number of injury crashes/year/street after the implementation of traffic calming.

The injuries resulting from these crashes were mostly minor, making up 88% out of the injured persons during the 'before' period and 75% during the 'after' period. There was one less slightly injured person reported after traffic calming initiatives were in place. However, the number of seriously injured persons/year/street grew from 0.03 to 0.06 (+100%).

The drop in injury crashes was anticipated, as the overall number of crashes had dipped. The jump in the number of persons with serious injury, however, does not necessarily mean that the traffic calming initiatives were ineffective. Since there were fewer injury crashes, it might only mean that there were more people, or vehicles with higher occupancy, involved in some of the crashes.

Furthermore, only four of the 28 streets recorded an increase in the number of injuries. There were more serious injuries, post-calming, on Grenville Street, Merivale Lane and Hastings Street. These are relatively long streets that intersect side roads and arterials, and have higher traffic volumes.

Table 4.18 – Injury and non-injury crashes before and after traffic calming

No.	Road	Analysis Period (years)	No. of injury crashes		No. of non-injury crashes	
			Before	After	Before	After
1	Aylesford Street	3	1	1	5	4
2	Francis Avenue	3	0	0	1	3
3	Stratford Street	6	1	1	3	1
4	Snowdon Road	5	0	0	1	1
5	Hamilton Avenue	3	2	1	1	2
6	Burke Street	3	0	0	0	2
7	Rattray Street	2	0	0	0	0
8	Kirkwood Avenue	3	2	1	2	2
9	Randolph Street	3	2	1	0	2
10	Mackenzie Avenue	2	1	1	3	2
11	Perry Street	3	0	0	0	0
12	Barbour Street	3	0	0	0	0
13	Grafton Street	2	0	0	2	1
14	Grenville Street	4	1	1	0	1
15	Baretta Street	4	0	0	1	1
16	Carrick Street	3	0	0	0	0
17	Flockton Street	3	0	0	1	3
18	Fairfield Avenue	3	2	0	1	3
19	Wherstead Road	6	0	0	0	0
20	Webb Street	6	0	0	1	0
21	Geraldine Street	6	2	1	3	3
22	Saltaire Street	4	1	0	2	2
23	Merivale Lane	7	1	5	3	1
24	Mary Street	6	3	1	7	5
25	Grants Road	6	2	2	7	3
26	Glenroy Street	3	2	1	1	0
27	Hastings Street	5	0	3	10	10
28	Wildberry Street	5	0	1	1	3
	Total	112	23	21	56	55
	Crashes/site/year		0.21	0.19	0.50	0.49

Table 4.19 – Serious and minor injuries before and after traffic calming

No.	Road	Analysis Period (years)	No. of injuries			
			Serious		Minor	
			Before	After	Before	After
1	Aylesford Street	3	0	0	1	1
2	Francis Avenue	3	0	0	0	0
3	Stratford Street	6	0	1	1	0
4	Snowdon Road	5	0	0	0	0
5	Hamilton Avenue	3	1	0	2	1
6	Burke Street	3	0	0	0	0
7	Rattray Street	2	0	0	0	0
8	Kirkwood Avenue	3	0	0	2	1
9	Randolph Street	3	1	0	1	1
10	Mackenzie Avenue	2	0	0	1	1
11	Perry Street	3	0	0	0	0
12	Barbour Street	3	0	0	0	0
13	Grafton Street	2	0	0	0	0
14	Grenville Street	4	0	3	1	2
15	Baretta Street	4	0	0	0	0
16	Carrick Street	3	0	0	0	0
17	Flockton Street	3	0	0	0	0
18	Fairfield Avenue	3	1	0	1	0
19	Wherstead Road	6	0	0	0	0
20	Webb Street	6	0	0	0	0
21	Geraldine Street	6	0	0	3	1
22	Saltaire Street	4	0	0	1	0
23	Merivale Lane	7	0	2	1	4
24	Mary Street	6	0	0	3	1
25	Grants Road	6	0	0	2	2
26	Glenroy Street	3	0	0	2	2
27	Hastings Street	5	0	1	0	2
28	Wildberry Street	5	0	0	0	2
	Total	112	3	7	22	21
	Injuries/year/street		0.03	0.06	0.20	0.19

These findings are not consistent with the pre-study hypothesis that there would be lower speed levels and hence fewer severe injuries after traffic calming. It should be noted that the severity of a crash does depend not only on the impact speed, but also on the type of collision, the crash-worthiness of the vehicle and whether the vehicle occupants were wearing safety belts or not.

While information on the crash-worthiness of vehicles and safety belt compliance was not available, the crash reports provided information on the collision types. It was found that rear-end collisions increased by 28.6%

during the 'after' period. Crossing or turning crashes were predominant during both 'before' and 'after' periods (46.8% and 43.0% respectively), followed by head-on crashes (25.4% and 22.8%), rear-end crashes (17.7% and 22.8%) and overtaking crashes (5.1% and 3.8%).

It is hard to attribute the increase in severe injuries to changes in collision type, because there were drops in collision types that could have had severe adverse consequences on the vehicle occupants.

Most of these crashes took place at intersections and this is mirrored by the high numbers of crossing or turning crashes. Intersection crashes are known to be more serious as they involve higher speed (vehicles on the main roads) and collision types that could result in more serious injuries, such as the abovementioned crossing or turning crashes, and pedestrian or cyclist crashes.

Intersections often have high pedestrian and cyclist activity, thus conflicts between vehicles and pedestrians or cyclists occur more often at these locations. As a result, there is not only a higher chance of crashes occurring at intersections, but also a higher chance of crashes involving pedestrians and cyclists resulting in serious injuries.

A study of crashes involving vulnerable road users was carried out, focusing on 10 streets that had pedestrian and cyclist related crashes reported before and after traffic calming measures were introduced.

It was found that cyclist crashes were higher than pedestrian crashes, both of which experienced increases of 25.0% and 28.6% respectively during the 'after' period (see *Table 4.20*).

It was also apparent that cyclist and pedestrian crashes occurred predominantly at intersections, with 13 out of the 16 cyclist-related crashes occurring at intersections, while the other three were at mid-block, with one of the crashes occurring off-road (i.e. on the footpath). Six out of the seven pedestrian-related crashes happened at intersections, while the other took place on the footpath at mid-block.

The increase in crashes involving vulnerable road users, particularly those involving cyclists was largely due to sharp rises in crash rates on Merivale Lane and Hasting Street. Also, considering that the traffic-calmed streets might have attracted more people to cycle and walk, there could have been increases in cyclist and pedestrian flows. This hypothesis, however, can only be validated by 'before' and 'after' flow data. Unfortunately, these data were not available.

Table 4.20 – Crashes involving vulnerable road users before and after traffic calming

No.	Road	Analysis Period (years)	No. of cyclist crashes		No. of pedestrian crashes	
			Before	After	Before	After
1	Aylesford Street	3	1	0	0	0
2	Stratford Street	6	1	0	0	0
3	Kirkwood Avenue	3	2	0	1	0
4	Randolph Street	3	0	1	0	0
5	Mackenzie Avenue	2	0	0	0	1
6	Fairfield Avenue	3	1	0	0	0
7	Geraldine Street	6	1	1	0	0
8	Merivale Lane	7	1	3	0	1
9	Mary Street	6	0	0	2	1
10	Hastings Street	5	0	4	0	1
	Total	44	7	9	3	4
	Crashes/year/street		0.16	0.20	0.07	0.09

The higher numbers of cyclist crashes did not come as a surprise, seeing as cyclists have to share the road with other vehicles, while pedestrians have segregated footpaths. However, pedestrian-vehicle conflicts do occur when pedestrians cross busy roads, mostly at intersections. This may explain why pedestrian-related crashes did not increase perceptibly at mid-block, but did at intersections.

Most of the cyclist crashes took place at intersections with major roads (i.e. street-ends). These occurrences were mostly due to drivers (exiting from and entering into local streets) not noticing cyclists making through movements at the intersections. From crash reports, most drivers blamed vehicle queues present on the major roads for their inability to notice the cyclists.

Pedestrian crashes mostly occurred at intersection crossings, where drivers had failed to observe pedestrians crossing on green. However, there were also instances when pedestrians were at fault. Two such cases involved pedestrians making unsafe crossings.

Four locations experienced increases in the number of pedestrian and cyclist crashes – Randolph Street, Mackenzie Avenue, Merivale Lane and Hastings Street. While the crash on Randolph Street involved two cyclists on the footpath, the crashes on the other three locations took place at busy intersections and involved contact with vehicles.

There was substantiation of the safety benefit of traffic calming measures specifically introduced to curb safety issues at intersections. This was demonstrated by the treatment given to the Kirkwood Avenue intersection with Ilam Road, which resulted in cyclist crashes being reduced from three to zero after an entrance treatment that featured a road narrowing combined with coloured paving blocks, was introduced.

The apparent increases in crash rates might be due to randomness or might follow a change in the pattern of flow in the network around the traffic calming scheme. The latter notion was tested through an area-wide crash analysis in Mairehau, comprising eight treated streets (i.e. the 'Flockton Cluster') and 22 untreated streets.

Unsurprisingly, the crash rate on the treated streets before treatment (2003 – 2005) was higher than for the untreated streets (0.33 crashes/year/street versus 0.18 crashes/year/street).

Crash rates during the 'after' period (2008 – 2010) remained higher on treated streets, with 0.46 crashes/year/street as opposed to 0.15 crashes/year/street recorded for untreated streets (see *Tables 4.21* and *4.22*).

This translated to a 39.4 % rise in crash rate on the treated streets after traffic calming. All crashes occurred on Aylesford Street, Flockton Street and Francis

Table 4.21 – Crashes in the Flockton Cluster (treated streets), Mairehau

No	Road	No. of midblock crashes		No. of intersection crashes		Total no. of crashes	
		Before	After	Before	After	Before	After
1	Aylesford Street	3	3	3	2	6	5
2	Francis Avenue (East)	0	1	1	2	1	3
3	Flockton Street	1	0	0	3	1	3
4	Carrick Street	0	0	0	0	0	0
5	Thornton Street	0	0	0	1*	0	1*
6	Archer Street	0	0	0	1*	0	1*
7	Speight Street	0	0	0	0	0	0
8	Squire Street	0	0	0	0	0	0
	Total	4	4	4	7	8	11
	Crashes/year/street	0.17	0.17	0.17	0.29	0.33	0.46

* Crash occurred at the intersection with Flockton Street and considered as crash on Flockton street

Table 4.22 – Crashes on the untreated streets in Mairehau

No	Road	No. of midblock crashes		No. of intersection crashes		Total no. of crashes	
		Before	After	Before	After	Before	After
1	Harrison Street	0	0	0	0	0	0
2	Crosby Street	0	0	0	0	0	0
3	Francis Avenue (West)	0	0	0	0	0	0
4	Pascoe Street	1	0	0	0	1	0
5	Kensington Street	0	4	2	3	2	7
6	Fergusson Ave	0	0	0	0	0	0
7	Patrick Street	0	1	0	0	0	1
8	Erin Crescent	0	0	0	0	0	0
9	Mahars Road	0	0	3	1	3	1
10	Greenwood Close	0	0	0	0	0	0
11	Manuka Street	0	0	0	0	0	0
12	Nancy Avenue	1	0	1	0	2	0
13	Norah Street	0	0	1*	0	1*	0
14	Ethne Street	0	0	0	0	0	0
15	Thames Street	0	0	1	0	1	0
16	Severn Street	0	0	0	0	0	0
17	Mersey Street	0	0	1	0	1	0
18	Malvern Street	0	0	0	0	0	0
19	Dee Street	0	0	0	1	0	1
20	Forfar Street	1	0	0	0	1	0
21	Mayfield Avenue	0	0	0	0	0	0
22	Berwick Street	1	0	0	0	1	0
	Total	4	5	8	5	12	10
	Crashes/year/street	0.06	0.08	0.12	0.08	0.18	0.15

* Crash occurred at intersection with Nancy Avenue and considered as crash on Nancy Avenue

Avenue (East). The high number of crashes on these streets is partly due to the higher volume of traffic these streets receive (see *Figure 4.33*). Furthermore, these streets intersect with highly trafficked arterials, which may explain why intersection crashes were higher than mid-block crashes.

For the same period, there was a 16.6 % drop in the crash rate on untreated streets, with only Kensington Avenue, Patrick Street and Dee Street experiencing more crashes. Six streets experienced reductions in crash rates, while the rest had not experienced any crashes during the analysis periods.

There was a drastic increase in the number of crashes on Kensington Avenue, particularly at mid-block. This street has the second highest volume of traffic, after Aylesford Street, and is also one of the longer streets in the network. Long streets with high traffic volumes tend to experience larger number of crashes than short streets with low traffic volumes.

Comparing the factors cited in crashes that occurred on treated and untreated streets, it was evident that speed-related crashes were more prevalent on treated streets, which gives justification for the implementation of traffic calming measures on these streets. This, in return, resulted in speed-related crashes dropping from three to two after traffic calming (see *Figure 4.34*).

The prevailing crash factors for both treated and untreated streets were quite similar, with poor observation, poor handling, and driving under the influence of alcohol being cited regularly.

However, there were more crashes due to failure to give way or stop, and poor judgement on untreated streets. These factors are typical errors committed by drivers at intersections.

Figure 4.33 – Daily traffic flows on streets in the area-wide study for the year 2011

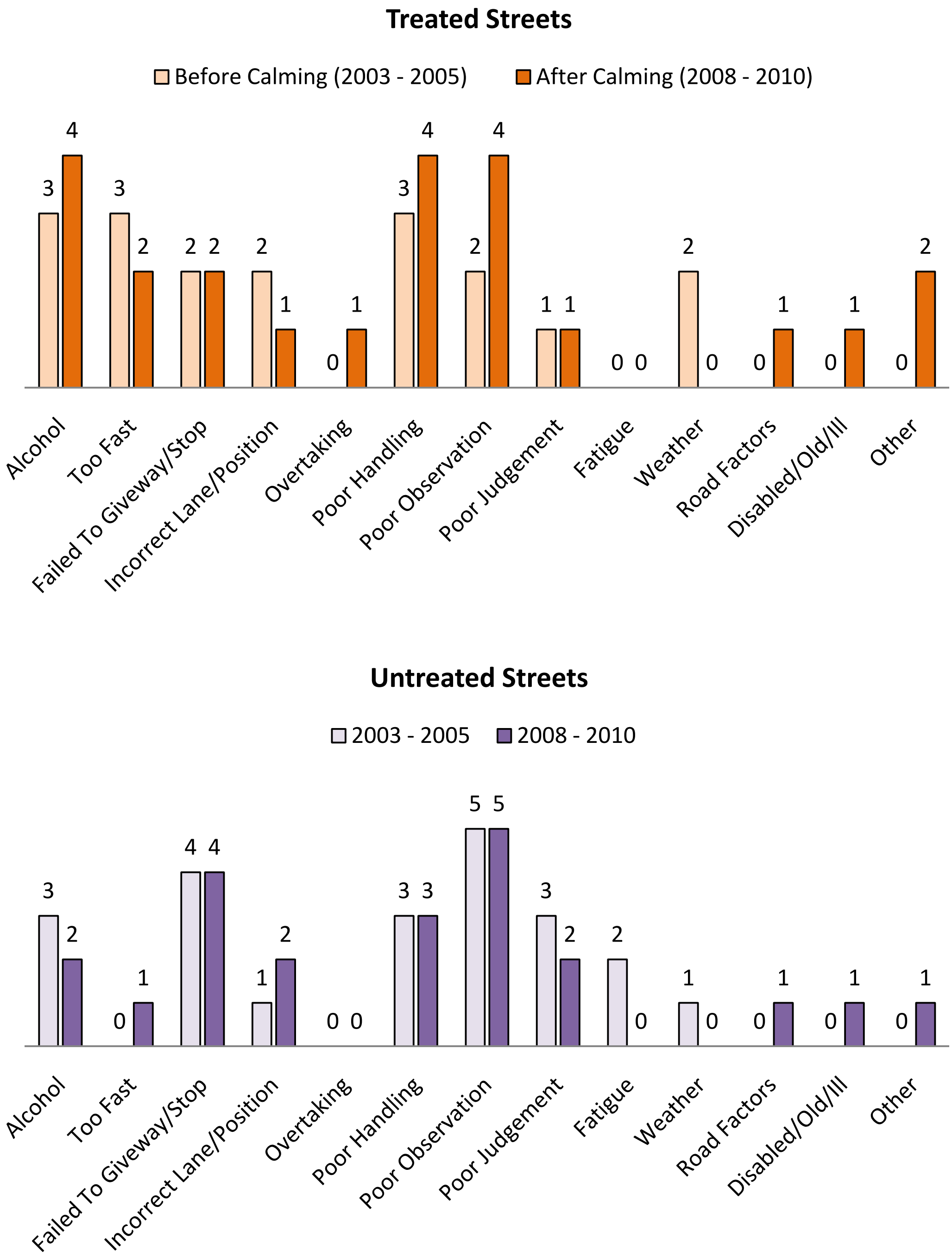


Figure 4.34 – Factors cited in crashes on streets studied in Mairehau

The objective of this area-wide study was to see if the rise in crashes on treated streets matched those on untreated streets in the same vicinity. It was found that the crash trend for treated and untreated streets showed no similarity and was actually the reverse of what one would have generally expected.

A further discussion on the findings of these crash analyses is provided in Section 5.4.

4.11 Idling engine noise and background noise

From the noise survey conducted on stationary light vehicles with engines left running (see *Table 4.23*), the idling engine noise, L_{idle} was determined as 51.1 dBA, with a standard deviation of 0.9 dBA.

The mix of vehicles was representative of light passenger vehicles surveyed in the vehicle noise studies alongside humps and a flat section of road. The year of manufacture for each surveyed vehicle was estimated as either during the 1990s or 2000s, seeing as details of the vehicles were not available. Nevertheless, the average age of the surveyed vehicles was reasonably representative of the average age of vehicles in New Zealand, i.e. 12.7 years (Ministry of Transport, 2011c).

Table 4.23 – Data for survey on idling engine noise

No.	Vehicle type	$L_{AF\,max}$ (dBA)	Vehicle make and Year
1	Car	50.37	Toyota Hatchback (1990s)
2	Car	51.76	Subaru Sedan (1990s)
3	Car	50.68	Nissan Sedan (1990s)
4	Car	51.44	Toyota Sedan (1990s)
5	Car	52.01	Subaru Wagon (1990s)
6	Car	49.96	Toyota Hatchback (2000s)
7	MPV	52.76	Honda Odyssey (2000s)
8	Car	51.42	Subaru Hatchback (1990s)
9	Car	50.38	Volkswagen Hatchback (2000s)
10	Car	51.08	Mazda Sedan (1990s)
11	Car	50.66	Toyota Hatchback (1990s)
12	Car	50.73	Toyota Sedan (2000s)
13	SUV	53.57	Daihatsu Feroza (1990s)
14	Car	50.23	Toyota Hatchback (2000s)
15	Car	51.46	Honda Sedan (1990s)
16	SUV	52.11	Toyota RAV4 (1990s)
17	Car	49.93	Mazda Hatchback (2000s)
18	Car	50.49	Nissan Sedan (1990s)
19	Car	50.04	Toyota Hatchback (2000s)
20	Car	50.68	Mazda Sedan (2000s)

Traffic along the road sections was mainly made up of light vehicles, with a very large portion being cars. This was followed by SUVs, vans, MPVs and trucks. There were no buses as these streets did not serve as bus routes. Information on traffic composition is provided in *Table 4.24*.

Table 4.24 – Traffic composition at the locations for noise studies

	Lochee Road		Wadeley Road
	Near hump	Near flat section	Near hump
Number of vehicles surveyed	256 (109)	266 (104)	444 (141)
Cars	82.0 (79.6)	82.7 (80.6)	71.6 (70.9)
MPVs	2.3 (2.2)	2.6 (3.9)	2.3 (2.0)
SUVs	8.6 (8.8)	7.1 (7.8)	18.0 (20.1)
Vans	5.1 (7.3)	6.4 (7.0)	5.6 (5.0)
Trucks	2.0 (2.2)	1.1 (0.8)	2.5 (2.0)
Light vehicles	98.0 (97.8)	98.9 (99.2)	97.5 (98.0)
Heavy vehicles	2.0 (2.2)	1.1 (0.8)	2.5 (2.0)
Vehicles towing trailers	4.3 (4.4)	1.9 (1.6)	2.0 (1.5)

Note: Apart from number of vehicles surveyed, all other values are stated as percentages. The values in parentheses are for traffic on the nearside lane, i.e. 7.5 m from the microphone.

The background noise was considered to be the noise level recorded during a traffic-free period. For the three locations, the background noise level averaged between 41 – 42 dBA, which was well below the maximum sound level during vehicle pass-bys (averaging above 60 dBA). This complies with the ISO 11819-1:1997 requirement of having at least 10 dBA differences. Results of the background noise surveys are shown in *Table 4.25*.

Table 4.25 – Background noise (dBA) recorded at the study locations

	Lochee Road		Wadeley Road
	Near hump	Near flat section	Near hump
Mean	41.1	41.7	41.4
Standard deviation	2.8	2.4	3.3
Minimum	37.5	37.1	34.4
Maximum	49.4	50.0	48.3

4.12 Comparison between noise levels produced by light vehicles on nearside and farside lanes

Noise and speed data were collected for nearside and farside lanes in order to estimate the differences in noise levels produced by light vehicles in both traffic directions.

For all the nearside lanes, the microphone was placed 7.5 m from the centre of the lanes. Since Wadeley Road was wider than Lochee Road, the distances between the microphone and the farside lanes were different, i.e. 11.7 m for the former, and 13.6 m for the latter.

Power functions were used to relate maximum noise level to speed. The estimated curves are shown in *Figures 4.35* to *4.37*. These relationships were found to be statistically significant, as can be deduced from the regression output in *Table 4.26*. The complete results are provided in *Appendix L*.

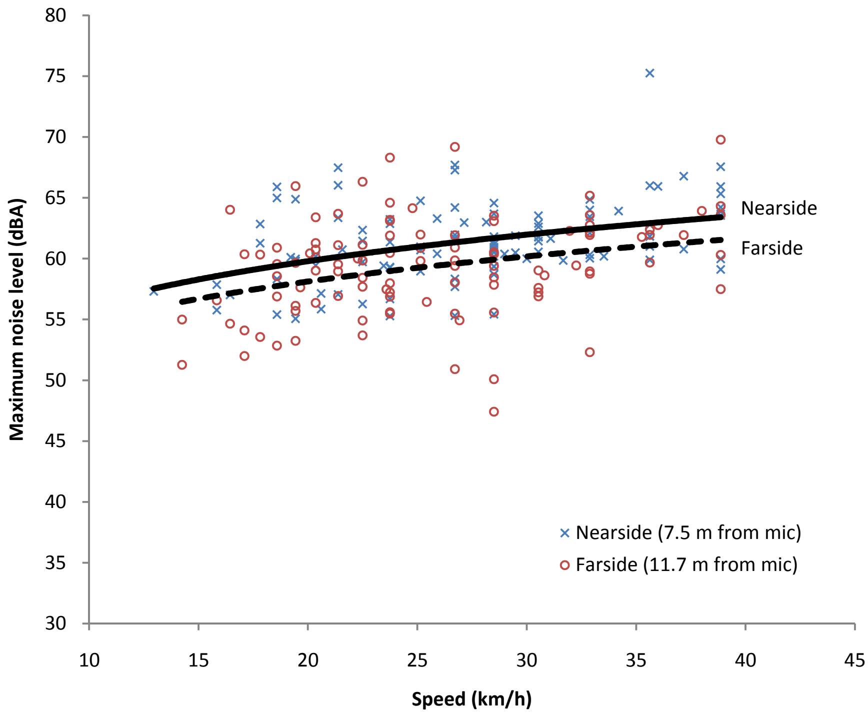


Figure 4.35 – Comparison between noise levels produced by light vehicles across a 75 mm speed hump on nearside and farside lanes

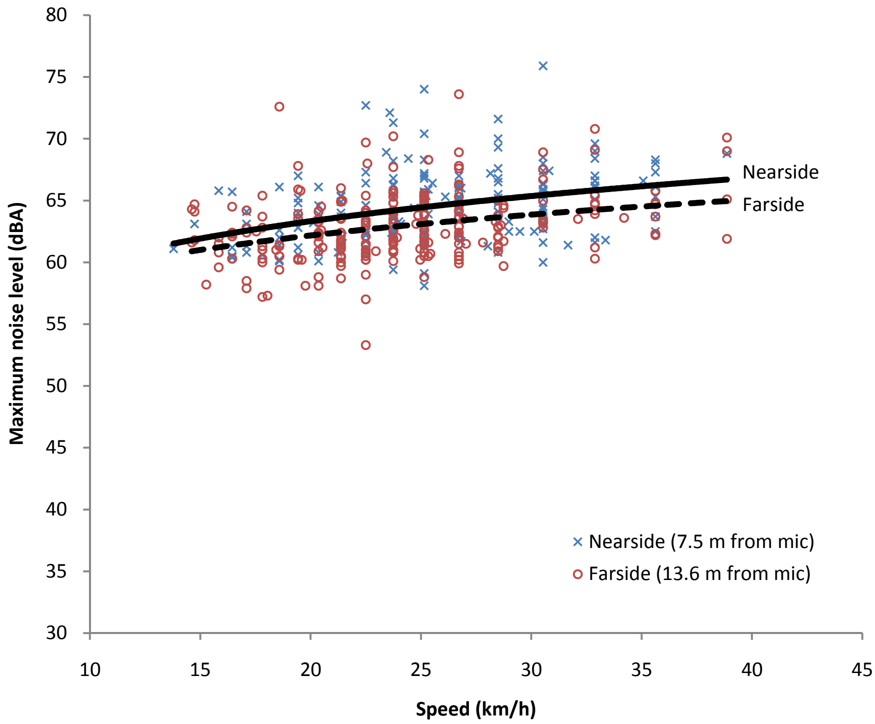


Figure 4.36 – Comparison between noise levels produced by light vehicles across a 100 mm speed hump on nearside and farside lanes

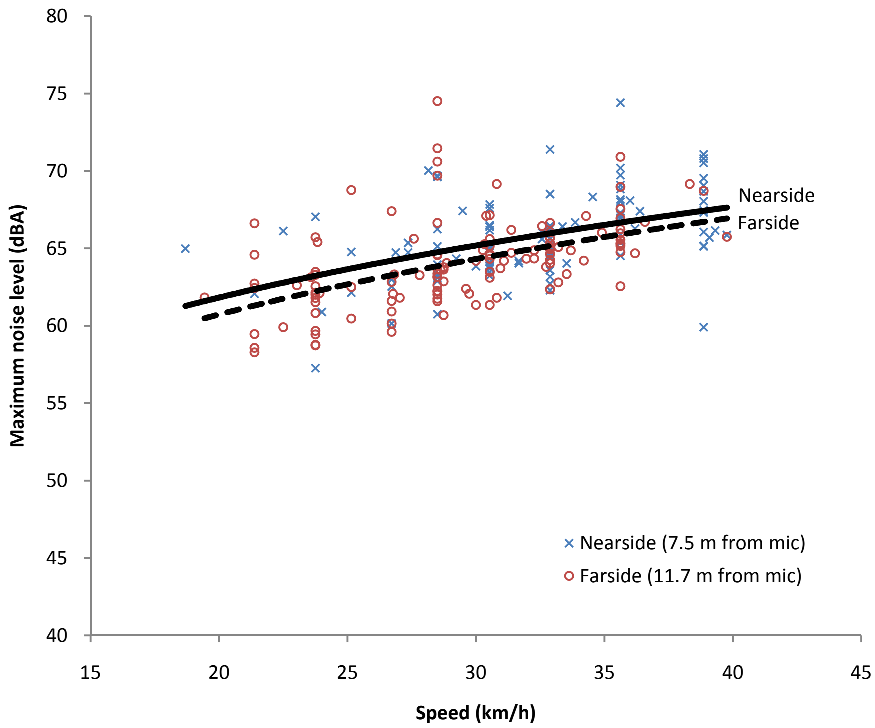


Figure 4.37 – Comparison between noise levels produced by light vehicles across a flat section of road on nearside and farside lanes

Table 4.26 – Output summary for maximum noise level and speed relationships on nearside and farside lanes

Model	SEE	*F*-statistic	Sig. *F*		Coefficients	*t*-statistic	Sig. *t*
Across 75 mm hump							
Nearside	0.048	20.635	0.000	Speed	0.088	4.543	0.000
				Constant	45.946	15.681	0.000
Farside	0.065	11.014	0.001	Speed	0.086	3.319	0.001
				Constant	44.895	11.939	0.000
Across 100 mm hump							
Nearside	0.041	28.356	0.000	Speed	0.078	5.325	0.000
				Constant	50.120	21.172	0.000
Farside	0.041	26.274	0.000	Speed	0.066	5.126	0.000
				Constant	51.019	24.546	0.000
Across flat section							
Nearside	0.038	25.687	0.000	Speed	0.131	5.068	0.000
				Constant	41.805	11.190	0.000
Farside	0.036	46.137	0.000	Speed	0.142	6.792	0.000
				Constant	39.659	14.163	0.000

SEE = standard error of the estimate, Sig. *F* = significance value of the *F*-statistic, Sig. *t* = significance value of the *t*-statistic

The estimated differences in noise levels produced by light vehicles travelling under 40 km/h on nearside and farside lanes were 1.6 – 1.9 dBA across the 75 mm hump, 0.8 – 1.7 dBA across the 100 mm hump, and 0.8 – 1.3 dBA across the flat section of road.

For observed mean speeds of 31.1 km/h across the 75 mm hump, 25.6 km/h (100 mm hump) and 34.9 km/h (flat section of road), the corresponding noise levels produced by light vehicles on the nearside lane were approximately 1.8 dBA, 1.3 dBA and 0.9 dBA higher than on the farside lane, respectively.

95% confidence intervals were calculated (see *Appendix M)* in order to inspect the range of values that act as good estimates of the maximum noise levels on nearside and farside lanes, and to ascertain whether the estimates for the lanes overlapped each other, thus suggesting that the differences were not significant. It was found that overlapping of the estimates existed close to the lower and upper speed limits, but it was not large. This implied that the differences in noise levels on nearside and farside lanes may to some extent be significant.

Subsequently, *t*-tests were performed to compare the means of maximum noise levels on nearside and farside lanes. Seeing as the *p*-values for the tests were close to zero, it was concluded that the means were significantly different (see *Appendix N*).

It should be noted that findings from this comparative analysis are aimed only at providing a rough estimate of the difference in maximum noise levels one would expect on adjacent travel lanes, and are not intended to establish the effect of distance on the attenuation of vehicle noise.

4.13 Noise produced by trucks and light vehicles towing trailers

During the surveys conducted on Lochee Road and Wadeley Road, small percentages of trucks (1.1 – 2.5%) and light vehicles towing trailers (1.9 – 4.3%) were observed. These vehicles were found to emit some of the loudest sounds measured.

The trucks produced maximum noise levels averaging 74.3 dBA and 75.0 dBA across the 75 mm and 100 mm humps respectively, while light vehicles towing trailers produced an average of 70.8 dBA (75 mm hump) and 78.6 dBA (100 mm hump).

Clearly, light vehicles towing trailers across the 100 mm hump produced the loudest noise, given the relatively greater height of the hump and operating speeds. It was observed that these loud noises originated mainly from the trailers and their loads. Trailers with loose loads were the noisiest.

As expected, the noise emitted by trucks and light vehicles towing trailers were louder across the speed humps than on a flat section of road. *Table 4.27* shows the means of the maximum noise levels produced by trucks and light vehicles towing trailers across the speed humps, in comparison with those produced over a flat section of road, along with the corresponding mean speeds.

Table 4.27 – Noise emitted by trucks and light vehicles towing trailers

	Mean of maximum noise levels		Mean speed	
	Trucks	Light vehicles towing trailers	Trucks	Light vehicles towing trailers
Across 75 mm hump	74.3	70.8	15.2	19.0
Across 100 mm hump	75.0	78.6	18.7	25.1
Across flat section	65.4	67.3	28.9	29.6

Vehicles towing trailers produced a considerable amount of additional noise when driven over speed humps, with significant increases of about 14 dBA and 12 dBA across the 100 mm and 75 mm speed humps respectively, and about 2 dBA over the flat section.

These additional noises (see *Table 4.28*) were obtained by comparing observed and estimated noise level using models developed in the subsequent section.

Table 4.28 – Additional noise produced by light vehicles towing trailers

	Mean speed (km/h)	**Max. noise level without trailer[a] (dBA)**	**Max. noise level with trailer[b] (dBA)**	**Approximate difference (dBA)**
Across 75 mm hump	19.0	59.0	70.8	12
Across 100 mm hump	25.1	64.3	78.6	14
Across flat section	29.6	65.0	67.3	2

Note: a – Predicted using the models, b – Mean observed maximum noise level

It should be noted that these findings were based on small sample sizes; therefore results may be different for roads with higher volumes of trucks or light vehicles towing trailers.

4.14 Vehicle noise prediction models on traffic-calmed streets

The noise differential models (ΔL_M) with regard to vehicle speed (V) were best explained using Power functions, which imply that noise levels will increase indefinitely with speed, albeit at a decreasing rate of increase.

By substituting these models and the idling engine noise into equation 3.12, the following equations for estimating maximum noise levels emitted by light vehicles traversing a 75 mm speed hump ($L_{ME(75)}$), a 100 mm speed hump ($L_{ME(100)}$), and a flat section of road ($L_{ME(flat)}$) were obtained:

$$L_{ME(75)} = 51.1 + 1.150V^{0.655} \tag{4.10}$$

$$L_{ME(100)} = 51.1 + 3.953V^{0.373} \tag{4.11}$$

$$L_{ME(flat)} = 51.1 + 3.549V^{0.404} \tag{4.12}$$

A summary of the regression analyses performed for the noise differential models is provided in *Table 4.29*.

The prediction models suggest that the maximum noise level produced when a light vehicle passes a 100 mm speed hump at a reference speed of 25 km/h is 3.6 dBA higher than when it passes a 75 mm hump.

Interestingly, the noise levels produced by light vehicles traversing a 100 mm speed hump are very close (±0.2 dBA) to those produced when traversing a flat section of a road at speeds under 50 km/h. This implies that, at equal speeds, the sound of a vehicle running over a 100 mm speed hump is almost identical to the sound of the same vehicle moving on a flat section of road (refer to *Figures 4.38* to *4.40*).

Figure 4.41 shows the noise level prediction curves and the comparison of noise levels for the mean travelling speeds recorded at the humps and the flat section. It was found that the noise produced by light vehicles traversing speed humps was actually lower than the noise produced while travelling on the flat section. This was an interesting finding as one would expect the opposite. Further discussion is provided in Section 5.2.4.

Spikes in noise levels were observed when light vehicles with trailers, and heavy vehicles moved over speed humps.

Table 4.29 – Output summary for noise differentials

Model Summary (75 mm hump)

R-square: 0.314 Standard Error: 0.307

ANOVA

F-statistic: 58.540 Significance: 0.000

Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	1.150	0.335	3.433	0.001
Vehicle speed	0.655	0.086	7.651	0.000

Model Summary (100 mm hump)

R-square: 0.146 Standard Error: 0.200

ANOVA

F-statistic: 32.443 Significance: 0.000

Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	3.953	0.837	4.725	0.000
Vehicle speed	0.373	0.066	5.696	0.000

Model Summary (Flat section)

R-square: 0.186 Standard Error: 0.179

ANOVA

F-statistic: 28.263 Significance: 0.000

Coefficients

	Coefficient	Standard Error	t-statistic	Significance
Constant	3.549	0.955	3.716	0.000
Vehicle speed	0.404	0.076	5.316	0.000

It was also established that light vehicles traversing the 100 mm hump produce higher noise levels than the 75 mm hump even though the speed at the 100 mm hump was lower than that at the 100 mm hump. This might be attributed to the steeper grade of the 100 mm hump that results in a more forceful rattling of the vehicle and to some extent decelerating and accelerating at higher rates.

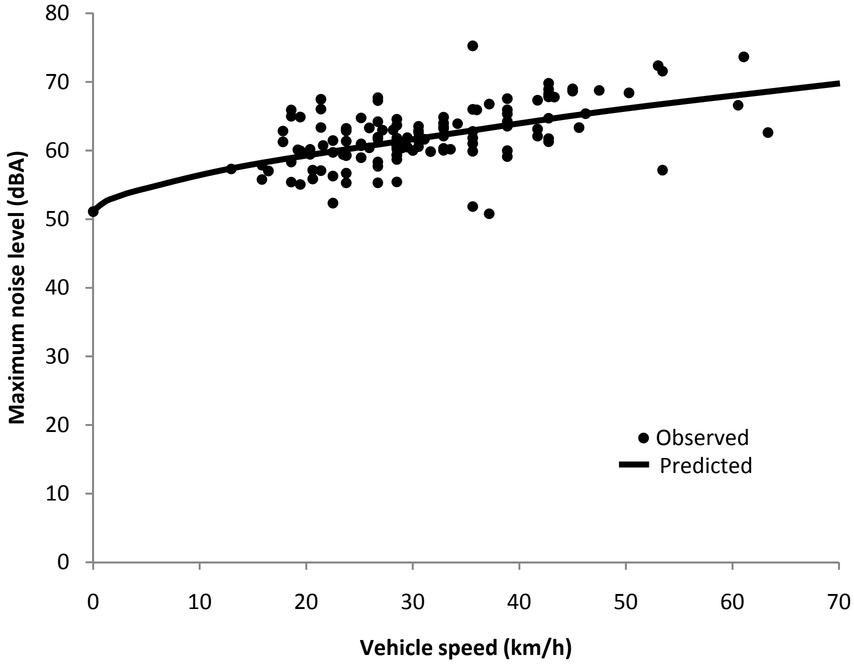


Figure 4.38 – Predicted and observed noise levels for a 75 mm speed hump

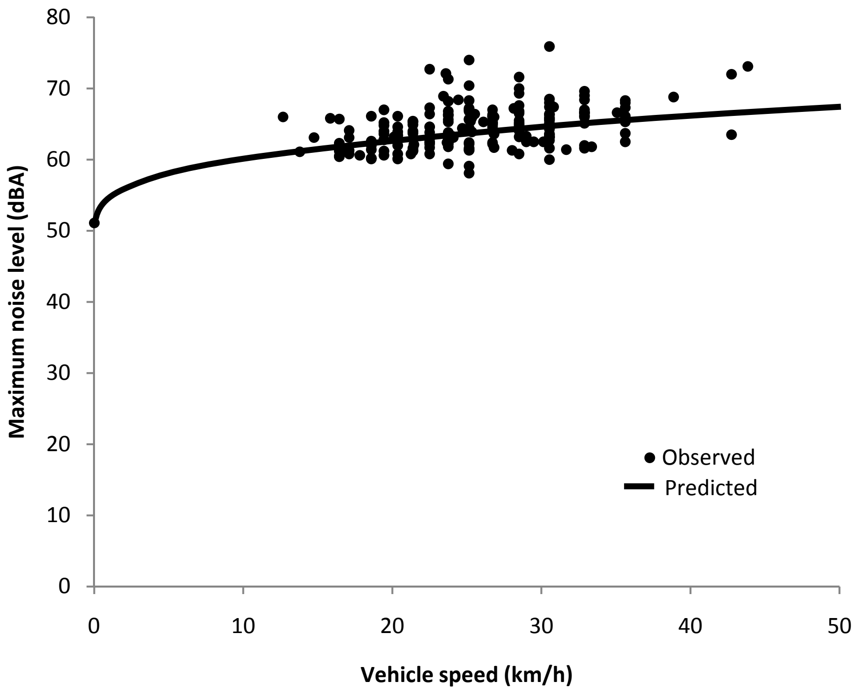


Figure 4.39 – Predicted and observed noise levels for a 100 mm speed hump

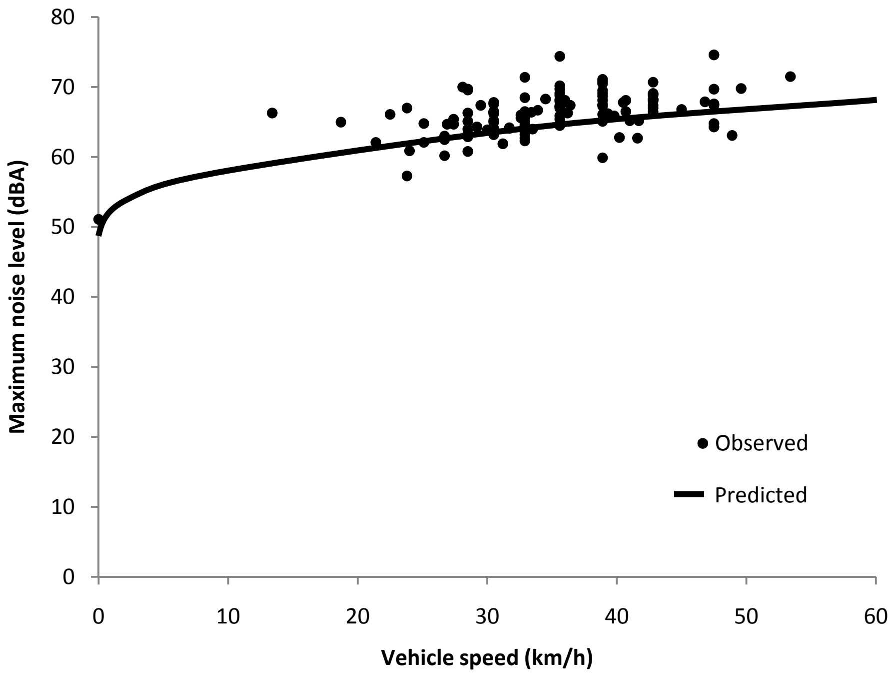


Figure 4.40 – Predicted and observed noise levels for a flat section

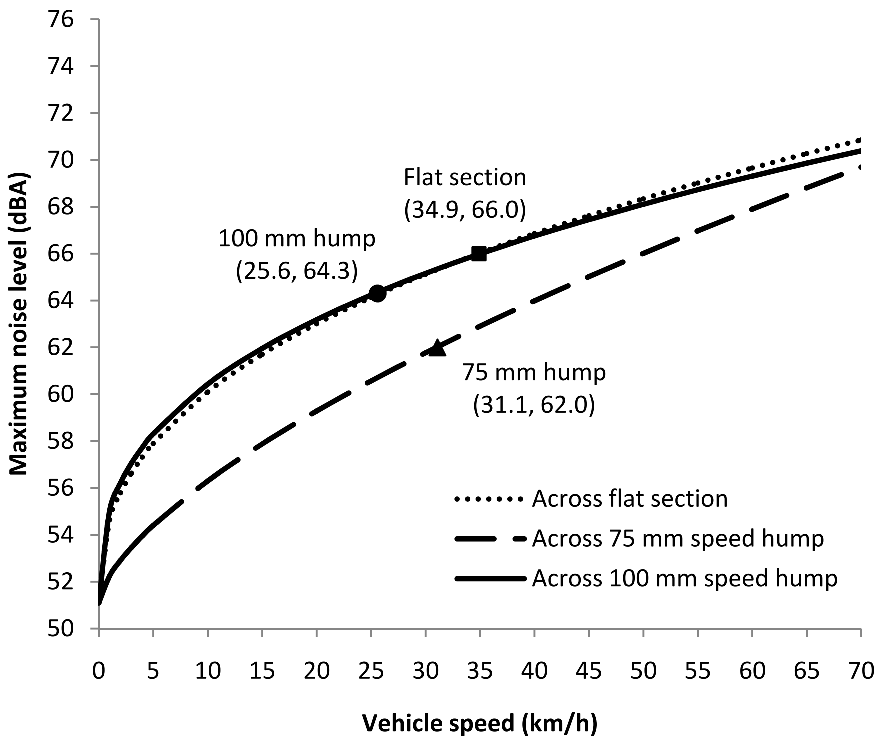


Figure 4.41 – Predicted noise levels for a street with speed humps

5 Discussion

This section features commentary on the findings of this research in comparison with published findings in the past, the factors that should be considered when conducting speed and noise studies, and constraints encountered during the undertaking of this research.

5.1 Comparing findings obtained from this research with those from past research

5.1.1 Device operating speeds

The operating speed of traffic calming devices is governed by driver behaviour and the geometry of the device, which in most cases varies from one street to another. Variation in the design characteristics of devices results in a range of operating speeds, thus making attempts to assign an operating speed for each device harder than it was thought to be.

Device operating speeds from this research were compared with those cited by Brindle (1999), resulting in some values falling within the range of values and some extending beyond the reported values (see *Figure 5.1*).

Clearly, the operating speed recorded for the 75 mm speed hump (42.2 km/h) was well outside the 30 – 35 km/h range of speeds reported by Brindle. The speed hump was a Watts profile hump that, given its smaller height and flatter ramps, provided only a small amount of discomfort when traversed at speeds greater than the design speed, which may explain why speeds observed across the hump were as high as 63.3 km/h.

Since the profiles of the speed humps cited in Brindle's report were not specified, it was not possible to determine whether profile type or length would have contributed to the lower operating speeds reported.

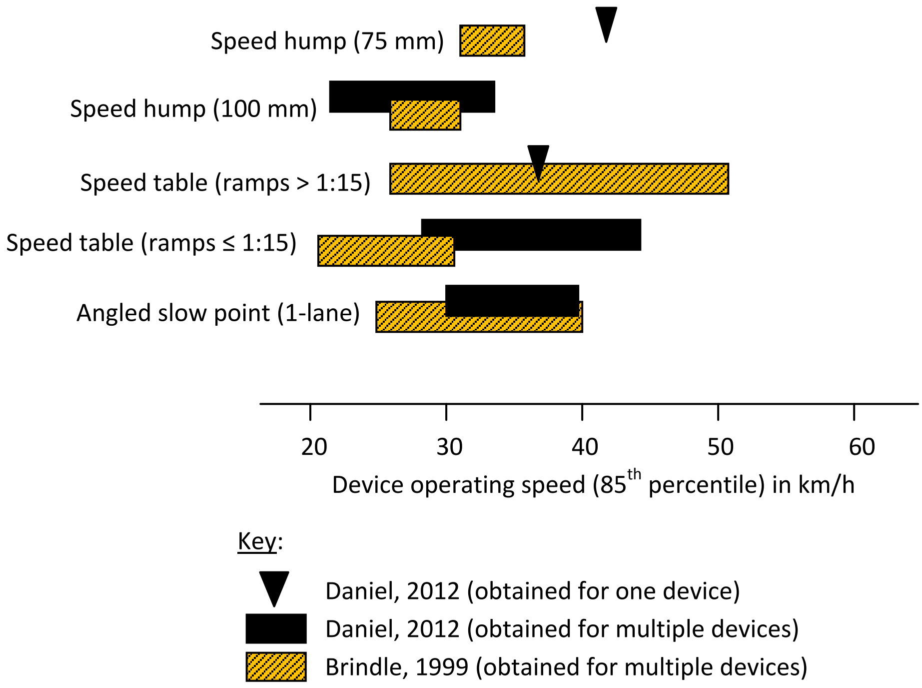


Figure 5.1 – Comparison with reported operating speeds for selected devices

For the 100 mm speed humps, the range of operating speeds was wider than reported by Brindle (1999), extending to as low as 21.9 km/h and as high as 33.9 km/h compared to the range reported by Brindle (25 – 30 km/h). Again, it was hard to say if profile type and length had actually caused the disparity in speeds, given that design specifics were not reported by Brindle.

The range of operating speeds for speed tables with ramp gradients up to 1:15 observed in this research were much higher than those cited in Brindle's report. It is suspected that the Brindle tables were probably greater in height than those studied in this research (i.e. 75 mm).

Despite not having a definite value for a particular type of device, the operating speeds reported in current and past work are of great importance as it gives an idea of how drivers would react to such a device. Moreover, these findings serve as a guide for practitioners. Nevertheless, it should be noted that even if replicating the design of a treatment, results may not necessarily be the same as there are other factors to consider, such as location and road users.

5.1.2 Appropriate placement of speed humps from a street entry or bend

The ITE (2007) guideline suggests that the spacing between the first hump and a stop sign (of an intersection) or a small-radius curve should be 200 ft (61 m) in order to prevent high approach speeds.

The approach speed model developed in this research is in agreement with the ITE guideline, as the model proposes that placing a hump 40 – 85 m from a street entry or a bend should ensure 85th percentile speeds between 35 – 40 km/h on the approach to the first hump in a series.

MRWA (2011) suggests that for a speed hump to operate efficiently and safely, the first hump should be placed 50 m from the start of the street where approach speed is low. This is also consistent with the findings of this research.

5.1.3 Zone of influence for single devices

The zone of influence produced by a traffic calming device varies according to device type. The zone of influence does not only represent the area over which a driver lowers the speed of his or her vehicle as he or she approaches a device, but also the area where speed recovers to its original level after traversing the device.

Brindle and Lydon (1998) reported that speeds had recovered 50 m after traversing flat-top speed humps (speed tables) and 70 m after traversing angled slow points.

The common agreement of findings from this research to Brindle and Lydon's was that the zone of influence for angled slow points was greater than that for speed tables. While this research produced a zone of influence of 55 m for the speed table, which did not deviate far from the 50 m reported by Brindle and Lydon, the raised and flush angled slow points produced values of 100 and 110 m respectively, which are higher than the 70 m reported by Brindle and Lydon.

This may be due to the angled slow points being single-lane, which required some drivers to stop and yield to oncoming traffic, hence a need to slow down far ahead of the device, and a longer acceleration distance required after coming to a halt.

5.1.4 Appropriate spacing for speed humps and speed tables

Austroads (2008) encourages hump spacings of 80 m to 120 m for achieving acceptable speed levels. This translates to 85th percentile speeds of 40 – 44 km/h using the speed- spacing relationship developed in this research.

ITE (2007) reports that speed humps placed 260 – 500 ft (79 – 152 m) apart will result in 85th percentile speeds ranging from 25 – 30 mph (40 – 48 km/h). The relationship from this study indicates 85th percentile speed values of 39.3 to 46.5 km/h, which are not much different from the ITE values.

The ITE guide also notes that 22-foot (6.7 m) long speed tables placed 300 – 500 ft (91 – 152 m) apart will produce 85th percentile speeds of 28 – 32 mph (45 – 52 km/h). Using the relationship developed in this research, 85th percentile speeds were estimated to be 43.5 – 48.6 km/h. The relatively narrow range is most likely due to the speed tables studied in this research having shorter lengths (3.6 – 5.0 m), thus resulting in lower speeds across and between the devices.

An Australian study by MRWA (1990) found that maximum 85th percentile speeds of approximately 40 km/h were achieved for spacings below 120 m, as opposed to spacings below 80 m found in this research. The MRWA study also revealed that maximum 85th percentile speeds below 30 km/h were achieved at spacings of 70 m to 80 m, in contrast to the findings of this research, which suggest that maximum 85th percentile speeds below 30 km/h are attainable if spacings of less than 25 m are provided.

The MRWA findings give the impression that Australian drivers are prepared to travel at low speeds with large spacings. This possibly reflects higher urban free speeds on untreated local streets in New Zealand; certainly the 85th

percentile urban speed for 50 km/h arterials in New Zealand is 57 km/h (Ministry of Transport, 2011b). However, it is important to note that MRWA assumes a lower device operating speed of 20 km/h, while the device operating speeds for humps in this study averaged 29.1 km/h.

Comparisons of models from this research with models produced by Webster (1993) using data from Great Britain are shown in *Figures 5.2* to *5.5*.

Another model that was developed by the California Traffic Control Devices Committee (ITE, 1997) for speed humps is included in the comparison shown in *Figure 5.2*.

For spacings of 140 m and below, the predicted 85th percentile speeds between speed humps for this study were rather similar to Webster's. However, the California model appears to underestimate the 85th percentile speed for spacings over 50 m.

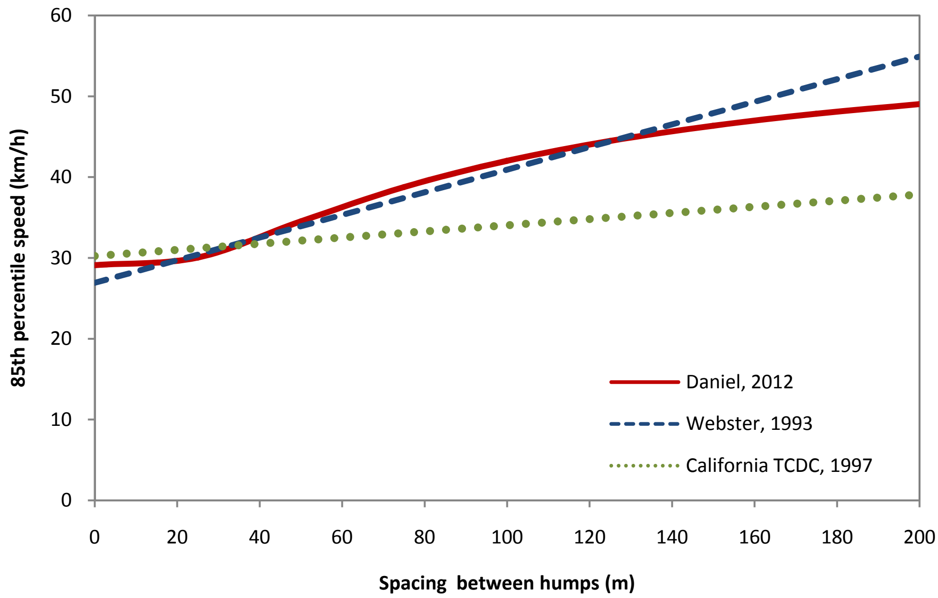


Figure 5.2 – Comparison of models for 85th percentile speed between speed humps

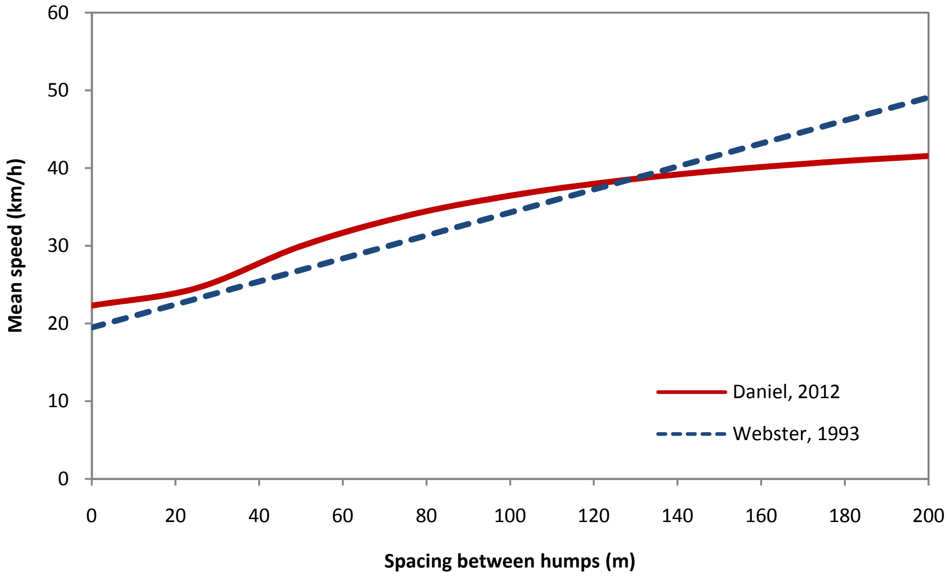


Figure 5.3 – Comparison of models for mean speed between speed humps

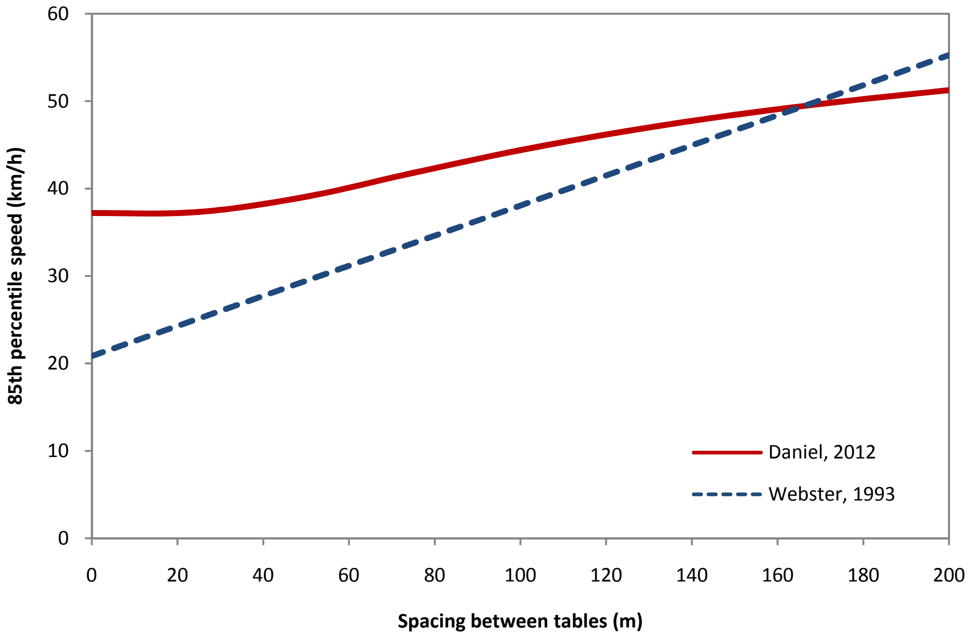


Figure 5.4 – Comparison of models for 85th percentile speed between speed tables

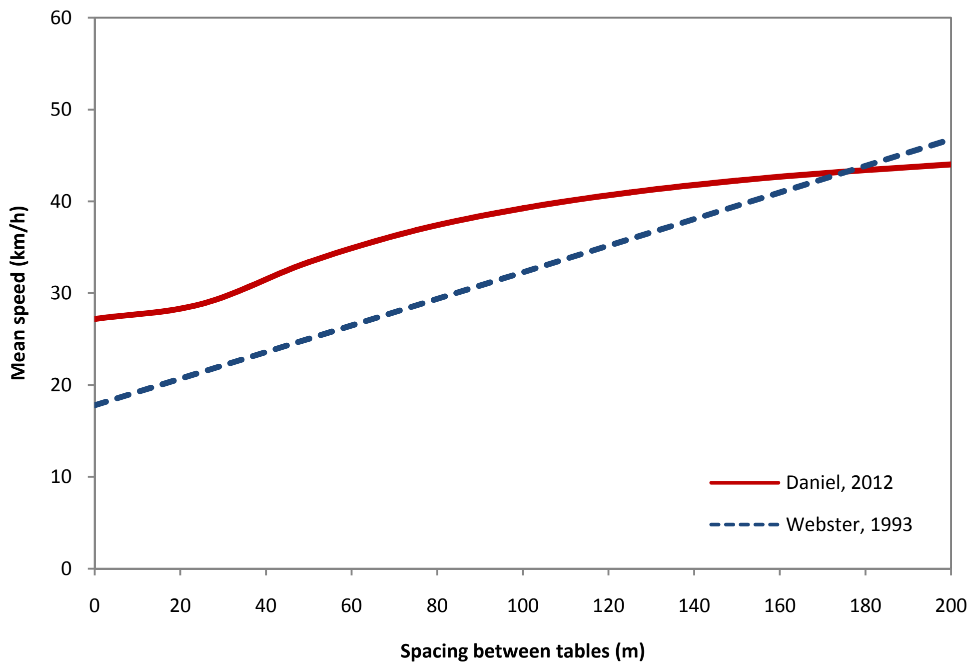


Figure 5.5 – Comparison of models for mean speed between speed tables

It can be seen from *Figure 5.3* that the predicted mean speeds were slightly higher than Webster's at spacings 130 m and below. At spacings 140 m and above, Webster's model predicts higher 85th percentile and mean speeds. This is due to the nature of the linear relationships adopted by Webster, which implies that speed increases indefinitely with spacing and therefore, larger spacings ultimately result in very high speed values.

The relationships developed for speed tables in this study vary substantially from Webster's models at spacings less than 170 m. It should be noted that the speed tables studied by Webster were 25 mm higher, but it is thought that device height has a marginal effect on speeds midway between devices. On the other hand, device height has a considerable effect on device operating speeds.

Webster (1999) reported that expected speeds between 80 mm humps (round-top and flat-top) are 5 and 2 mph (8.0 and 3.2 km/h) higher for 85th percentile speed and mean speed respectively at zero spacing, and approximately the same when spacing is 150 m, compared to 100 mm humps.

Operating speeds at speed tables were noticeably higher compared to those in Great Britain, mainly due to the tables having lower heights and, one suspects, smoother transitions.

5.1.5 Noise emitted by light vehicles across speed humps

Comparing the vehicle noise emission models developed in this research with those of Abbott et al. (1995), who used logarithmic functions, it was observed that the noise levels in this study were quite similar at 25 km/h, but lower at speeds over 25 km/h (see *Figure 5.6*). The lower noise levels at speeds over 25 km/h were probably due to engineering and technological advancements in the automotive industry since the Abbott et al. study, resulting in more effective control of engine and tire-road noise emissions.

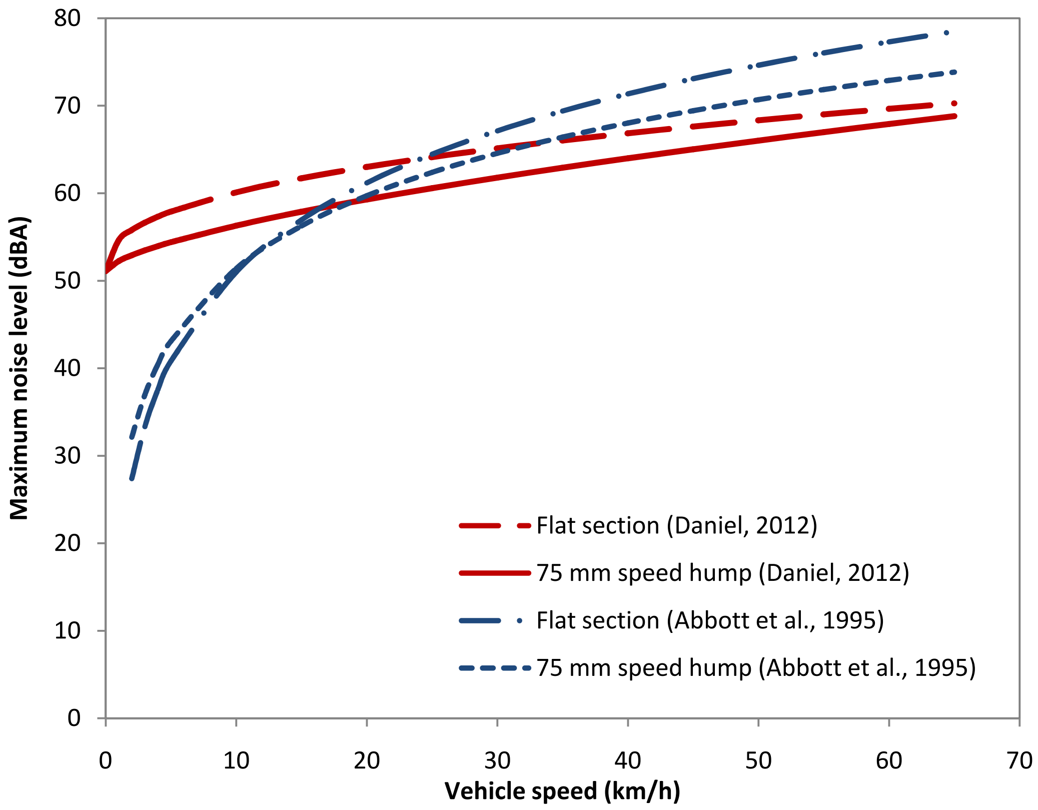


Figure 5.6 – Comparison of noise models

Unlike the Abbott et al. models, which have noise levels tending to zero as speed tends to zero, these new models tend towards the idling noise level. Thus, the Abbott et al. models may not offer good predictions at lower speeds, mainly due to the nature of the logarithmic function.

The models developed in this research, on the other hand, are practical as they correspond to actual noise levels produced at various speeds more aptly. These models would benefit practitioners who wish to gain information on noise impacts of speed humps not only on residential streets with conventional speed limits, but also on 10 km/h or 20 km/h streets that are often used as shared-spaces.

5.2 Factors that influence vehicle speed and noise

5.2.1 Device operating speed

It has been established that the geometry of a traffic calming device governs the speeds at which vehicles operate over it. For vertical deflections, such as speed humps and speed tables, device height has a more significant influence than width and length. The greater the height, the lower the operating speed will be. This is reflected in the comparison of the 75 mm and 100 mm speed humps, in which the 100 mm humps produced a lower operating speed.

Another controlling factor for speed tables is ramp gradient, which depends on the height and length of the device. Steeper ramps, which produce a higher discomfort level when traversed at high speeds, are thus more likely to result in lower operating speeds.

Apart from device height and ramp gradient, device width with respect to road width was found to have a small but significant influence on operating speed.

The street speed, which is the 85th percentile speed at unimpeded segments, may also have an effect on the device operating speed. Vehicles travelling at higher speeds were observed to operate at higher speeds at the devices than those travelling at lower speeds.

For devices placed in a series, device spacing is an important influencing factor. Devices placed closer to each other generally produce lower device operating speeds due to the limited space for speed recovery.

However, there are other factors that may influence the speed that drivers decide on when traversing speed control devices. The type, age and condition of a vehicle may, to some extent, affect speed choice.

Drivers of SUV-type vehicles such as four-wheel drive (4WD) and newer vehicles are more likely to travel at higher speeds over these devices. Apart from that, one suspects that drivers of older vehicles are more likely to travel at lower speeds due to the condition of the vehicle. This may also be true for drivers of heavy vehicles, particularly those carrying goods.

The presence of traffic signs that inform drivers about devices ahead or that are placed at the devices, and speed advisory signs, may also play a part in drivers' choice of speed.

5.2.2 Street speed

The street speed is the speed on sections that are not restrained by speed control devices. The street speed was taken as the highest 85th percentile speed recorded, and should not be equated with the free speed of a conventional residential street, i.e. one that has no speed control measures.

Where devices were used in a series, the street speed was broken down into two types; the approach speed (speed on the approach to the first device in a series) and inter-device speed (speed between devices).

A driver's choice of speed on a conventional residential street may be influenced by road geometric factors such as the roadway width, road alignment and the length of the street. Apart from that, non-roadway factors such as the presence of buildings, trees, parked vehicles, and the distance of housing from the road have been found to reduce urban vehicle speeds (Martens et al., 1997).

It is believed that the perceptual width of the road, established by the presence of roadside objects such as trees and utility poles, may cause drivers to think they are travelling faster than they actually are. Drivers are therefore more inclined to drive slower on streets with narrower perceptual widths (Fildes & Jarvis, 1994).

When a traffic calming device is installed on a street, the presence of the device becomes a major factor in deciding travel speed. The type of device has a considerable effect on approach and inter-device speeds, with vertical deflections more likely to produce lower street speeds than horizontal deflections would.

The approach speed is further influenced by the approach length, which is the available distance between the device and the street entry or bend. Likewise, the inter-device speed is regulated by the spacing between the devices.

Other factors that may affect street speed are on-street parking, and the number and type of access points (i.e. private driveways and side roads). The presence of cars parked by the kerbside can greatly influence street speed, especially when the street width is narrow to moderate, and when parking density (i.e. number of cars parked per distance) is high. This is due to the lessening in effective width, i.e. the amount of pavement that is available for drivers to use.

The presence of access points may also influence street speed. Streets with high access point density (i.e. number of access points per distance) are more likely to produce lower street speeds due to drivers anticipating the ingress and egress of vehicles.

5.2.3 Zone of influence

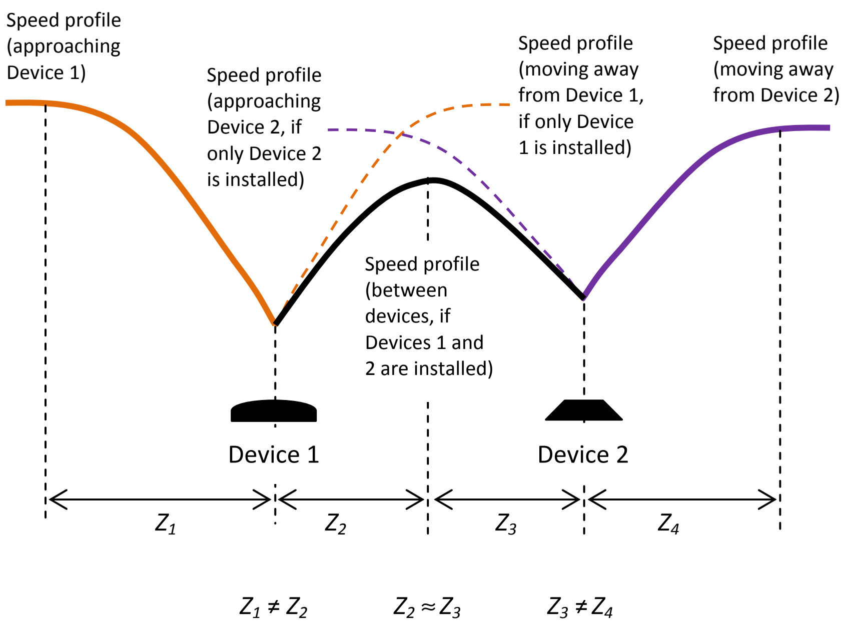
When approaching a traffic calming device, drivers choose to start slowing down at various distances from the device. It is hard to pinpoint what factors motivate them to choose that distance simply because it is impossible to tell what is going through their minds at that time. Hence, predicting the distance where drivers would normally start slowing down using speed profiles is the next best means to gauge their zone of influence.

It is suspected that the zone of influence for an isolated device depends mainly on the type of device and the approach distance. It has been found that narrowings exerted the smallest zone of influence compared to other devices. Angled slow points had the largest zone of influence, followed by the speed table and the speed hump.

Approach distance had a considerable effect, with smaller approach distances producing smaller zones of influence as a result of lower approach speeds. Hence, approach speeds may also be a factor in determining the zone of influence, with lower approach speeds requiring less space for drivers to slow down to their desired device operating speeds. The speed-distance relationship obtained in this study showed that higher speeds are expected for longer approaches. However, it should be noted that some drivers may choose lower speeds even on long approaches.

When distances of the devices from the street entries are equal, the total zone of influence for isolated devices would be approximately twice the zone of influence per direction. The same, however, cannot be said when the aforesaid distances are unequal or for devices used in a series.

The zone of influence produced between two consecutive devices is atypical from one that is produced by an isolated device, especially when spacing between the two devices is close. The zone of influence between two devices was mostly observed to be half of the spacing between them. This was generated as a result of the overlapping of individual zones of influence for each device (see *Figure 5.7*).



Note: Assuming Devices 1 and 2 are different, hence $Z_1 \neq Z_4$

Figure 5.7 – Formation of zones of influence (z_i) between two consecutive devices

However, at larger spacings (≥ 200 m), the overlapping of individual zones of influence may not take place as sufficient space may be available for vehicles to recover to their original street speed prior to slowing to cross the next device. This was observed for King Street, where the speed humps were 200 m apart and the individual zones of influence between the humps were approximately 70 m, and not 100 m as one would expect (see *Figure 5.8*).

The configuration of the King Street speed humps exemplifies the effect of approach length and spacing on the zone of influence. Note that, on the longer approach, the zone of influence was greater. Also, the zones of influence on the approaches were more than the 50 m observed for the single speed hump on Burke Street (refer to section 4.4). This was due to the shorter approach and lower approach speed on Burke Street.

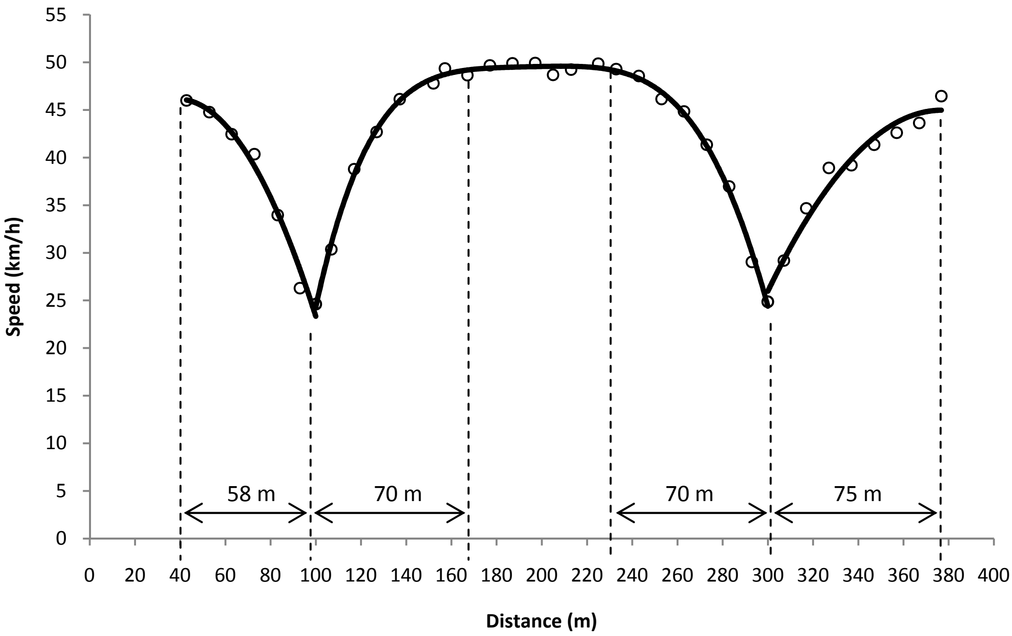


Figure 5.8 – Zones of influence between two consecutive devices with large spacing (200 m) on King Street

5.2.4 Noise levels

In this research, noise levels were predicted using speed as the sole predictor variable. While it is evident that speed has a major influence on vehicle noise emission (i.e. higher speeds produce higher levels of engine, tyre-road and air friction noise), other factors (such as vehicle age and condition, engine type and pavement type) may also influence noise levels produced by vehicles.

Older vehicles and vehicles that have been poorly maintained produce more noise than newer, well-serviced and technologically-advanced vehicles. The louder noise emitted by older and poorly maintained vehicles can be attributed to the mechanical condition of the car, such as old engine and tyres, and impaired suspension and braking systems.

The type of engine a vehicle runs on also contributes to the operating noise of the vehicle. Naturally, vehicles with engines running on diesel are noisier than petrol powered engines, due to the combustion process that produces noise commonly known as diesel clatter.

The type of pavement governs the noise produced by tyre-road interaction. Pavement roughness and porosity are key factors that influence the level of tyre-road noise. Open graded porous asphalt (OGPA) is approximately 2 dB quieter than conventional asphaltic concrete (AC) pavements, while chip seal surfaces can be up to 6 dB louder than AC pavements (Dravitzki & Kvatch, 2007).

The sound descriptor used in this research, the maximum noise level (L_{AFmax}) is generally for outdoor living areas, i.e. the sound a person sitting on his or her veranda or garden would hear when a vehicle passes by. Therefore, it should not be interpreted as the sound level one would expect indoors. Generally, the level of sound originating from outside a house is much lower indoors. For a normal building, outdoor sound levels decay by up to 20 dB when the windows are closed or at most 15 dB when the window is partly ajar (Lynch & Hack, 1984). This is due to the attenuation of sound, existence of sound barriers, and sound insulation provided by walls, windows and curtains.

This research found that the maximum sound level a light vehicle would emit while crossing a speed hump is 62 – 64 dBA, assuming that the vehicle is travelling at the mean operating speed. The noise level is in fact 2 – 4 dBA lower than when the vehicle travels on a flat section at a mean street speed. This might seem somewhat surprising because speed humps have acquired a reputation for causing more noise.

Although these noise levels are categorised as ‘moderate’, and are comparable with the sound levels produced during a normal conversation (60 – 65 dBA), repeated exposure to sounds produced as a result of vehicle pass-bys may cause annoyance.

It should be noted that these sound levels are for light vehicles. Heavy vehicles and light vehicles towing trailers produce noise levels of up to 14 dBA higher than light vehicles.

The lower noise levels observed across the humps were mainly attributed to the lower operating speeds. On the flat section, speeds were higher, thus resulting in higher engine, tyre-road and air friction noise.

The effect of surface texture might have been one of the key reasons for the higher noise levels on the flat section. The surface of the flat section was coarser than the surface of the humps. Chip seal surfaces can be 3 – 6 dBA louder than asphaltic concrete surfaces (Dravitzki & Kvatch, 2007) while Austroads (2003) suggests that chip seal (or spray seal) surfaces are 2 – 4 dBA louder than asphalt surfaces.

It should also be noted that the noise measurements for the humps and the flat section were not conducted simultaneously. Therefore, the differences in vehicle condition and driving style might have had some bearing on the differences in noise levels.

The noise observed across the humps mostly originated from the noise produced when the tyres hit the humps and landed back on the pavement, and from vehicle body rattling. This suggests that the noise produced when light vehicles ride on and off the humps is compensated by the reduction in noise resulting from lower travelling speeds, and the reduced tyre-road noise due to the smoother surface of the humps.

Vehicle acceleration and deceleration in the vicinity of the humps have an impact on vehicle noise emission. Lelong & Michelet (1999) explain that the effect of acceleration on emitted sound levels is perceptible at low speeds when mechanical noise is predominant. For passenger cars, strong accelerations (aggressive driving) can increase noise levels by up to 5 dBA.

However, during this study, the majority of the drivers drove their vehicles calmly along the street and therefore, large increases in noise levels due to acceleration of vehicles were not commonly observed.

Then, there is also the question of whether the acceleration and deceleration processes involved when negotiating a speed control device actually reduces or increases road traffic noise. This was addressed by Kokowski & Makarewicz

(2006), who found that there was a 0.4 dBA net reduction in noise levels as a result of decelerating on the approach to, and accelerating away from a 100 mm flat-top speed hump. It should be noted that the sound produced across the device was not considered in their study.

The impact of vertical speed control devices on environmental noise may vary from one location to another, depending on the traffic composition, vehicle condition and driving behaviour.

The speed hump is a highly effective traffic calming tool and when circumstances necessitate the use of such a device, consideration should be given in its design and placement, so as to mitigate potential noise issues. The planting of trees or shrubs alongside a speed hump, and the placement of a speed hump adjacent to existing fences may offset any noise increase, while the placement of a speed hump next to open spaces such as fields may minimise the number of impacted residents.

5.3 Commentary on variation in drivers' choice of speed on traffic-calmed streets

This research attempted to examine how drivers react to various traffic calming devices through the study of speed profiles of individual drivers, which resulted in valuable information about drivers' speed choice on approach to, over, and away from the devices, and how certain devices were able to produce small variations in device operating speeds, while others did not.

It was found that vertical deflections altered drivers' choice of speed rather significantly seeing as the device operating speeds were considerably lower than the street speeds (highest 85th percentile speed on the unimpeded segment). Drivers were also more inclined to continue at a lower speed after traversing vertical deflections.

The same, however, could not be said about horizontal devices. Drivers did not appear to be bothered by narrowed travel paths. Their speed choice was very similar on the unimpeded and impeded sections.

Drivers did, however, reduce their speeds when a vertical deflection was combined with a horizontal deflection. The speed profiles were similar to those produced for vertical deflections alone, thus implying that vertical deflections are more effective tools for lowering speeds than horizontal deflections.

The study of speed variation observed at traffic calming devices showed that the speed hump and the raised one-lane angled slow point produced significantly lower variations in speed across the devices than on the unimpeded sections.

It is likely that the drivers' reaction to the speed hump was largely influenced by the 'less forgiving' design, which considerably impairs riding comfort when traversed at high speeds.

While the raised one-lane angled slow point had an effect similar to the speed hump, the flush variant did not. This suggests that combining a platform with a deflected path will more likely produce smaller variations in device operating speeds.

Larger variations in device operating speeds were observed across the speed table and the raised one-lane narrowing, implying that drivers are divided when it comes to deciding on their speeds across these devices.

The 'more forgiving' design of speed tables, which allows better ride comfort than speed humps, is perhaps the main reason why some drivers maintain their speeds when traversing speed tables.

Drivers negotiating the raised one-lane narrowing were probably not bothered by the 50 mm platform and constriction, particularly when there was no oncoming traffic. Therefore, very small reductions in vehicle speeds were observed across this device.

Given that the device operating speeds were about the same as the street speeds for flush narrowings, the variations in speed at the device were equal to those on unimpeded segments. This suggests that drivers were only slightly affected by the constriction of the roadway and chose to maintain their speeds along the streets.

When selecting a traffic calming scheme for a street, the performance of the device (in reducing speeds) is often considered along with other factors such as cost and community response.

This research proposes that the performance of a traffic calming device should be based not solely on its ability to reduce speed, but should also take into consideration the variation in device operating speeds it produces.

In other words, an effective traffic calming device should not only yield low operating speeds, but small variations in operating speeds.

5.4 Commentary on findings of the safety impact study

The findings from the crash analyses performed on the 28 traffic-calmed streets gave no clear indication that, when there was an increase in crash rates, it was associated with the traffic calming measures implemented. Crashes are, after all, random multi-factor events that are more likely to be associated with human factors than road environment factors.

There was some evidence to support the safety benefits of traffic calming, such as the 50% drop in speed-related crashes, and the intersection safety improvement on Kirkwood Avenue.

However, there was no evidence to suggest that the increases in pedestrian and cyclist crashes were the result of traffic calming measures not being able to provide safer conditions for non-motorised travel, as the human factor and issues regarding conspicuity were found to have played a major role in causing most of these crashes.

Overall, the safety impact studies conducted on the 28 traffic-calmed streets and within the Mairehau road network were rather inconclusive in terms of identifying the effect of traffic calming on road safety.

Although there was evidence that demonstrated the safety benefits of traffic calming, there were also issues pertaining to the rise in crash rates post-calming. This, however, could not be directly linked to traffic calming and may be due solely to the randomness of crashes.

Even with treatments aimed at slowing and managing traffic, there are no guarantees of reductions in crash rates as drivers may still commit errors and be influenced by other factors such as vehicle and road environment factors, weather and lighting.

Also, the effect of traffic calming measures may differ from one location to another. Therefore, attempting to establish the safety benefit from traffic calming may produce mixed results, as in this study.

It is acknowledged that the safety study had limitations, namely the small crash numbers even when aggregated, and factors that were not accounted for, e.g. changes in volumes.

5.5 Practical applications of this research

The research findings presented in Chapter 4 may be used by practitioners, local councils and/or software developers in either one or a combination of the following ways:

(a) As a guide to good practices, particularly in the evaluation, selection and placement of traffic calming devices that effectively reduce vehicle speeds to desired levels.

(b) Estimation of 85^{th} percentile and mean speeds on traffic-calmed streets (i.e. at the device, on the approach to the first device in sequence and between two consecutive devices) using the speed prediction models.

(c) Estimation of maximum noise levels emitted by light vehicles across 75 mm and 100 mm speed humps, and across flat sections of the road using the noise prediction models.

(d) As an add-on to existing traffic analysis software, or development of new local area traffic management software that enables practitioners to analyse the impacts of traffic calming devices on local and collector streets.

5.2.1 Example of application: Oakhampton Street

This section discusses an actual situation that involves a street requiring speed control measures and explains how findings of this research can be applied in the planning of traffic calming schemes.

Oakhampton Street is a local street in the suburb of Hornby, Christchurch (see *Figure 5.9*) that is 9.3 m wide and is extraordinarily long (680 m).

A speed survey conducted on the street in September 2011 revealed that the 85th percentile and mean speeds were 56.4 km/h and 48.6 km/h respectively. The speed profile is shown in *Figure 5.10*.

During the survey, a few residents had approached the observer and complained about drivers travelling at high speeds. Their grievance was justified as it was observed that vehicle speeds were as high as 82.7 km/h.

The residents suggested using speed humps to deter speeding, a solution that practitioners would generally agree on. But how many humps should be used for such a long local street, and how far apart should they be? This can be resolved based on findings of this research.

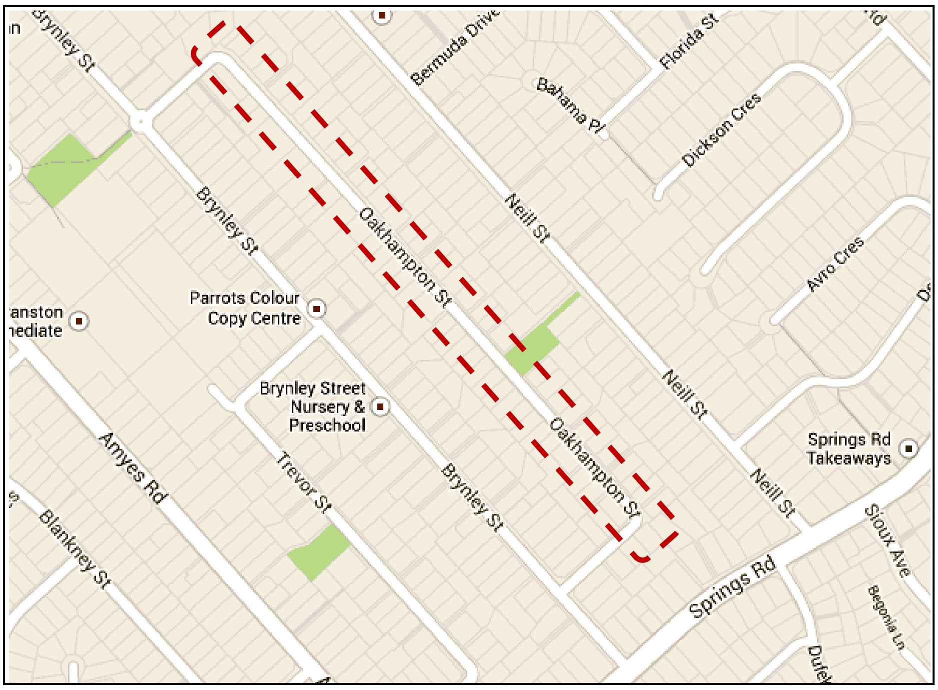


Figure 5.9 – Map showing Oakhampton Street

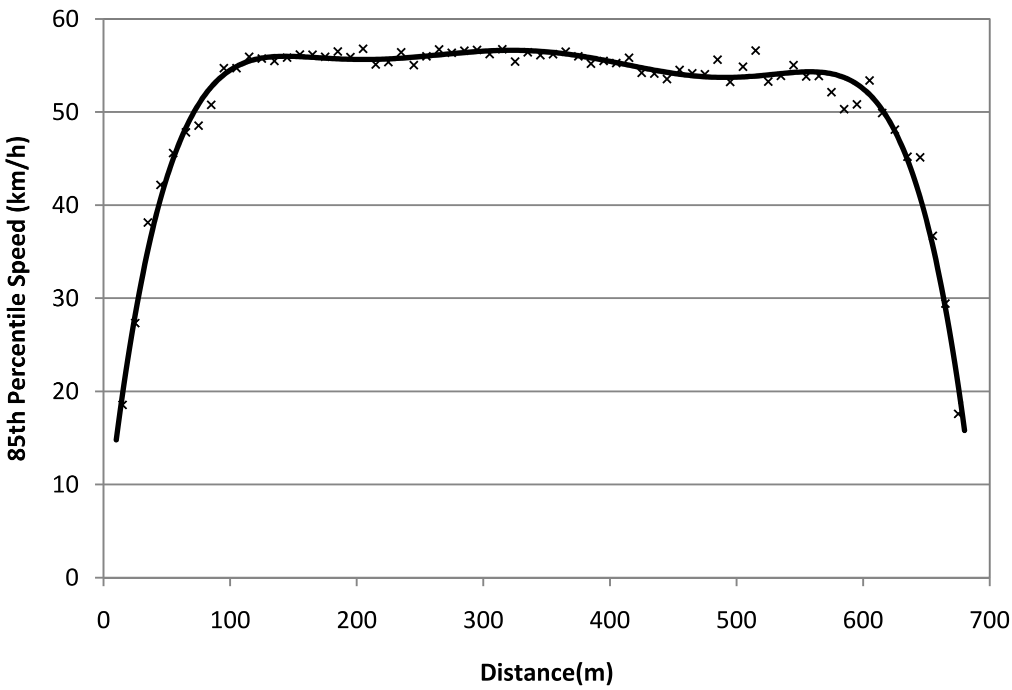


Figure 5.10 – Speed profile obtained for Oakhampton Street

A set of three 100 mm speed humps placed at 140 m from the bends and 200 m between the humps (see *Figure 5.11*) is proposed for Oakhampton Street and tested using the models developed in this research to see if vehicle speeds can be lowered.

Based on findings (refer to *Table 4.4*), the device operating speed for 100 mm speed humps is taken as 30.5 km/h.

Using *Figure 4.27*, the estimated highest 85th percentile speed on the approaches (segments bounded by the bends and the first and third humps) is about 43.0 km/h, while the estimated highest 85th percentile speed between two consecutive humps using *Figure 4.30* is approximately 50 km/h.

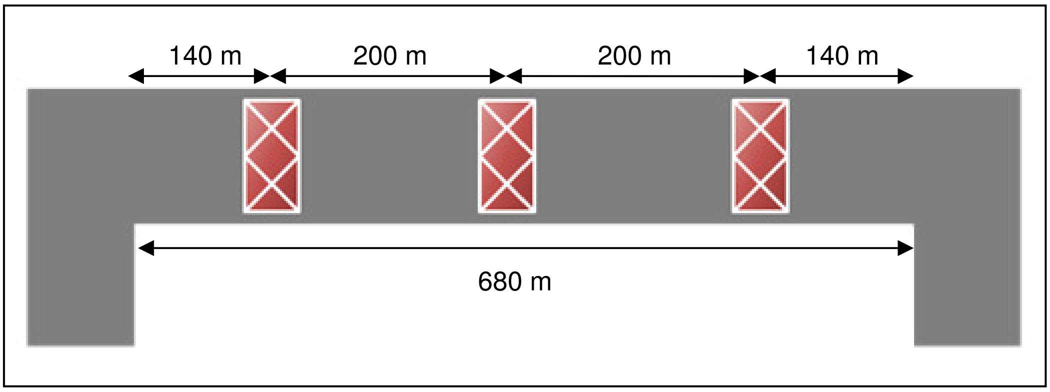


Figure 5.11 – The suggested placement of three speed humps on Oakhampton Street

The critical points (i.e. the device operating speeds, and the highest 85th percentile speeds on the approach and between the devices) govern the shape of the speed profile. Thus, the projected speed profile as a result of the implementation of the traffic calming scheme can be sketched (see *Figure 5.12*).

The proposed configuration of the speed humps can be accepted, seeing that the projected 85th percentile speeds along Oakhampton Street post-calming do not exceed the 50 km/h speed limit. Certainly, adding a fourth speed hump would result in the speed profile being lowered by a few notches given that speed declines with spacing. However, if there is a budgetary constraint, the local council can be assured that the use of three speed humps in sequence is good enough to reduce speeds and ultimately deter speeding.

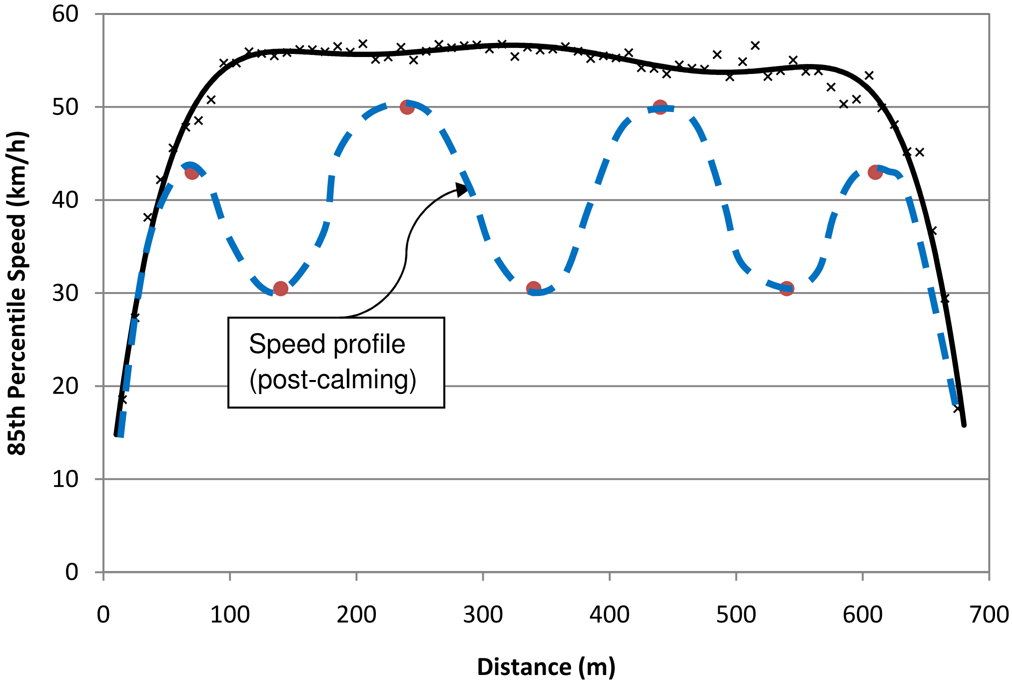


Figure 5.12 – Expected change in speed profile for Oakhampton Street post-calming

With regards to vehicle noise emissions, *Table 5.1* summarises the maximum outdoor noise levels across the speed hump and flat sections of the road that were estimated using the noise prediction models (refer to equations 4.11 and 4.12).

Table 5.1 – Estimated speeds and outdoor noise emission levels on Oakhampton Street post-calming

	85th Percentile Speed (km/h)	Maximum outdoor noise levels* (dBA)
Across 100 mm hump	30.5	65.2
Across flat section (between humps)	50.0	68.3
Across flat section (on approaches)	43.0	67.3

* Indoors, these noise levels should decay by up to 20 dBA (Lynch & Hack, 1984)

5.6 Limitations of this research

While the studies conducted in this research were successfully carried out with no major setbacks that would have adversely affected the outcomes, there were some constraints that were beyond the control of the researcher.

The major earthquakes that struck Christchurch in September 2010 and February 2011 had forced the planned before-and-after traffic calming studies to be cancelled as street renewal projects had to be shelved in order to accommodate recovery works.

Fortunately, the majority of the data used for other analyses were collected prior to the earthquakes, although there were a few conducted after. In order to eliminate the effect that the quake aftermath would have had on driving behaviour, these studies were carried out several months later when the situation had improved. In addition, these studies were conducted on streets that were not damaged by the quakes.

In the initial stages of this research, there were intentions to investigate the impacts of traffic calming devices on vehicle exhaust emissions and driver attitude. However, as time progressed, the direction of this research changed with much emphasis given to speed, noise and safety studies. Time (including delays as a result of the major earthquakes) did not permit further studies of the impacts on air quality and driver behaviour.

Another limitation to this research was the availability of the same type of devices. There were not many devices available for study, in particular, horizontal deflections, such as narrowings and angled slow points used in a series. Consequently, studies on the effect of spacing between these horizontal deflections on inter-device speed could not be performed.

Finally, noise studies on the speed tables that were readily available could not be conducted due to spatial restrictions (the inability to achieve the standard 7.5 m separation of the sound level meter from the source) and potential noise intrusion from adjacent roads.

5.7 Summary

Discussions were made in this chapter to acknowledge other factors that may have influenced traffic speed, safety and noise emissions. These factors, however, could not be investigated due to certain limitations.

This chapter also provided an opportunity to explain the inconclusiveness of the safety study, and the surprising revelation that noise levels across flat road sections were almost the same as those across 100 mm speed humps and higher than those across 75 mm speed humps.

Furthermore, comparisons were made with previous research to emphasise that the analytical methods and findings of this research, particularly the speed and noise prediction models, were innovative and relatively more pragmatic.

6 Conclusion

This chapter summarises the key findings obtained from this research and highlights the main contributions to the state of the art. In addition, suggestions for future research are also discussed.

6.1 Research conclusions

This research was aimed at investigating the impacts of neighbourhood traffic management on speed choice, road safety and traffic noise by evaluating the performances of traffic calming devices, and obtaining ways of estimating speed and noise on traffic-calmed streets. The objectives of this research have since been met and its accomplishment is confirmed through the following conclusions:

(a) 85^{th} percentile speeds at long distances from traffic calming devices were higher for streets controlled by horizontal deflections (about 45 – 55 km/h) than for streets controlled by vertical deflections (about 40 – 45 km/h).

(b) Drivers were more inclined to alter their travel speeds to lower levels after traversing devices involving vertical deflection, than for devices involving horizontal deflection. Faster drivers had more pronounced speed reductions. However, they negotiated the devices at higher operating speeds than slower drivers. This was observed from speed profiles of individual drivers.

(c) The 100 mm speed hump produced the lowest device operating speed (21.9 km/h). This device was also most influential in reducing street speed, as shown by the substantial speed change and small variation in speeds.

(d) The speed table produced a low device operating speed, but did not perform as well as the speed hump. Though street speeds were kept below the 50 km/h speed limit, the device operating speed was approximately 13 km/h higher than the speed hump. The gentler design of the speed table enabled drivers to operate their vehicles at higher speeds, thus leading to a larger variation in speed at the device than at the speed hump.

(e) The one-lane raised angled slow point produced a greater speed-reducing effect than the speed table (operating speed 30.0 km/h), and just like the speed hump, the variation in speed was smaller than on other sections of the street. However, street speeds were still fairly high.

(f) Of the narrowings, the one-lane raised variant reduced speed moderately (3.5 km/h), while the wider and flush variants produced only slight differences between device operating speeds and street speeds (between 1.3 km/h and 2.6 km/h).

(g) Statistically significant decreases in mean speed were observed at the speed hump, the speed table, the raised and flush angled slow points, and the raised narrowing. On the other hand, the flush narrowings did not produce statistically significant decreases in mean speed.

(h) Angled slow points exerted the most extensive zones of influence (100 – 110 m), meaning that drivers began reducing speeds at further distances from the device compared to other devices. By contrast, drivers chose to slow down at a closer distance to the speed hump and speed table (50 – 55 m), and narrowings (40 – 45 m).

(i) The zone of influence for speed humps was found to be controlled by the available space on the approach and the speed on the approach. Longer approaches and higher speeds yielded wider zones of influence. It was also found that approach speed was higher on longer approaches.

(j) The device operating speed for speed humps was found to be influenced by the ratio of the hump width to the road width. Smaller ratios produced lower operating speeds.

(k) Placing a speed hump 40 – 85 m from a street entry or a bend should ensure 85th percentile speeds between 35 – 40 km/h on the approach to the hump.

(l) Placing two speed humps 50 – 80 m and 80 – 130 m apart is likely to result in 85th percentile speeds of 35 – 40 km/h and 40 – 45 km/h respectively at the mid-point between the devices.

(m) Placing two speed tables 55 – 105 m apart is likely to produce 85th percentile speeds within the 40 – 45 km/h range at the mid-point between the devices.

(n) A slight drop in the overall crash rate was observed after the implementation of traffic calming measures on 28 streets studied. There were more crashes at intersections than there were at mid-block. However, the intersection crash rate fell and the mid-block crash rate increased after traffic calming. There was no clear evidence that any increase in crash rates was associated with traffic calming devices.

(o) Light vehicles produced less noise across speed humps (AC surface) than on the flat section of road (chip sealed), given their respective mean travelling speeds.

(p) The sound level a light vehicle would emit while crossing a speed hump was around 62 – 64 dBA, assuming that it was travelling at the mean operating speed. The noise level was in fact about 2 – 4 dBA lower than for a vehicle travelling on a flat section at a mean street speed. At equal speeds below 50 km/h, the noise levels produced by a light vehicle crossing a 100 mm speed hump (AC surface) were not very different from when it travelled on a flat section of road (chip sealed). This, however, may not be true if similar AC surfaces are used.

(q) The difference in noise levels for light vehicles travelling at speeds up to 40 km/h on the nearside and farside lanes was estimated to be no more than 1.9 dBA over the 75 mm speed hump, 1.7 dBA (100 mm speed hump) and 1.3 dBA (flat section).

(r) At a reference speed of 25 km/h, the noise levels produced by light vehicles across the 100 mm hump were 3.6 dBA higher than those produced over the 75 mm hump. Light vehicles produced less noise when crossing the 75 mm speed hump compared to the 100 mm speed hump. However, in terms of speed reduction, the 100 mm speed hump was more effective, with mean speed 5.5 km/h lower than the 75 mm speed hump.

6.2 Contributions to the state of the art

Considering the fairly innovative methods introduced and significant findings produced by this research, it can be established that the following contributions have been made to the state of the art:

(a) An in-depth look into the speed and noise impacts of traffic calming devices in New Zealand, which serves as a guide not only to practitioners in Australasia but also other parts of the world.

(b) A set of speed profiles for the estimation of 85th percentile speeds, mean speeds and anticipated speed reductions that may be attained by the use of various traffic calming devices. This is an expansion of the speed profiles presented in Austroads' *Guide to Traffic Management: Part 8: Local Area Traffic Management*.

(c) Additional guidance for the selection of traffic calming devices to suit desired speed reduction levels, the placement of speed humps from street entries or bends to manage approach speeds, and the appropriate spacing of speed humps and speed tables to regulate inter-device speeds.

(d) A different outlook on the effectiveness of traffic calming devices that calls for the inclusion of the assessment on speed variance at the devices, as opposed to basing the performance solely on speed reduction. This research suggests that an effective device should ideally produce low operating speeds, coupled with a small speed variance.

(e) A model that associates device operating speed with the ratio of speed hump width to road width, which provides a guide for the design of speed humps that are to be installed partially across a street.

(f) Speed prediction models that allow for the estimation of speeds on the approach to speed humps, and speeds between consecutive speed humps and speed tables. These models are more realistic compared to previous models by Webster (1993) and ITE (1997) (refer to Section 5.1.4).

(g) Models for predicting maximum noise levels emitted by light vehicles traversing 75 mm and 100 mm speed humps, and a flat section of road. These models are more diverse and pragmatic compared to a previous model developed Abbott et al (1995) (refer to Section 5.1.5).

(h) Where there is a constraint in obtaining pre-calming data for streets that have been traffic-calmed, the method proposed by this research, i.e. the comparison of existing street speed and device operating speed, may be applied to evaluate the effectiveness of the devices.

(i) Analytical methods for the development of logical speed and noise models using non-linear regression, with consideration given to fixing the y-intercepts as realistic speed and noise values that correspond to zero distance or zero speed respectively, and regulating the shape of the estimated curves particularly at large distances or speeds.

6.3 Recommendations for future research

The following are work that could potentially be explored:

(a) Given that engineering solutions alone are often not enough to control speeds in neighbourhoods, there is a better chance of achieving low speed environments if 30 km/h or 40 km/h speed zones are imposed on local streets, supported by the use of traffic calming devices. It is therefore recommended that before-after studies be conducted in these zones, with and without traffic calming, and on conventional local streets (50 km/h speed limit) with traffic calming, in order to gauge the combined and separate contributions of lower speed limit, and traffic calming devices.

(b) Since this research was focused on streets with 50 km/h speed limits, the findings may not necessarily be applicable to streets with lower speed limits (30 km/h or 40 km/h) because street speeds will most likely decrease. Therefore, in conjunction with the recommendation in (a), the research design and analytical methods implemented in this research may be emulated for streets with 30 km/h or 40 km/h speed limits.

(c) Given that efforts to obtain statistically significant speed models for the estimation of speeds on the approach to speed tables were unsuccessful due to the limited range of observed approach lengths, a new set of data covering a larger range of values is essential. This presents an opportunity for follow-up studies that adopts the research design and analytical methods proposed in this research, not only for speed tables but for other devices such as speed cushions, angled slow points and narrowings.

(d) The research design and analytical methods used for developing speed-spacing models may also be applied in studying the influence of spacing on other traffic calming devices used in a series.

(e) Noise emitted by buses and trucks when traversing vertical speed control devices are particularly useful for local streets that are bus routes and have abnormally high numbers of trucks (possibly due to short-cutting), and also for collectors and arterials (although vertical deflections are not commonly used here). Therefore further work can be carried out by means of the research design and analytical method introduced in this research.

(f) Due to the limitations in the study of safety impacts and the inconclusiveness of the results from the crash data analyis, a greater range of analyses needs to be carried out to better understand the safety implications of traffic calming measures. It is recommended that studies that attempt to relate safety awareness pre- and post-calming with road user expectations and attitudes (based on type of users, age, gender, familiarity of route, etc.) are carried out. Apart from this, Nilsson's Power model (1982) may be applied in studying the relationship between crashes and speed before and after the installation of calming devices.

(g) A study on the impact of traffic calming devices on vehicle exhaust emissions can be carried out to investigate claims of reduced air quality as a result of such devices, particularly vertical deflections. Since key findings about this issue were made more than a decade ago (Boulter & Webster, 1999; Boulter & Hickman, 2001), it would be essential to have a more current understanding as technological improvements have been made to vehicle exhaust systems and the design of vertical deflections have evolved.

(h) Given that traffic calming ultimately alters driver behaviour, thus a deeper understanding of what goes through the minds of drivers when approaching and negotiating traffic calming devices will be of great use. It is therefore recommended that an in-depth psychological study on drivers' perceptions and attitude towards traffic calming be conducted.

6.4 Summary

This research has produced several noteworthy findings that include the establishment of some practical guidance for the evaluation, selection and placement of traffic calming devices, and the development of realistic prediction models for the estimation of vehicle speeds and noise emissions along traffic-calmed streets.

Apart from this, the research design and analytical methods implemented in this research can be applied by other researchers who are interested in these studies, but strongly believe that findings from this research may not necessarily correspond closely with the different conditions (i.e. driver behaviour, transport policies and traffic regulations) in their respective localities.

7 References

Aarts, L. & van Schagen, I., 2006, *Driving Speed and the Risk of Road Crashes: A Review,* Accident Analysis and Prevention, Vol. 38, No. 2, pp. 215-224.

Abbott, P., Tyler, J., & Layfield, R., 1995, *Traffic Calming: Vehicle Noise Emissions Alongside Speed Control Cushions and Road Humps*, TRL Report No. 180, Transportation Research Laboratory (TRL), Crowthorne, Berkshire.

Abbott, P., Taylor, M., & Layfield, R., 1997, *The Effect of Traffic Calming Measures on Vehicle and Traffic Noise*, Traffic Engineering and Control, Vol. 38 No.9, pp. 447-453.

Ajzen, I., 1991, *The Theory of Planned Behaviour*, Organisational Behaviour and Human Decision Processes, Vol. 50, pp. 179-211.

Almqvist, S. & Nygard, M., 1997, *Dynamic Speed Adaptation: A Field Trial with Automatic Speed Adaptation in an Urban Area*, Bulletin 154, Department of Traffic Planning and Engineering, University of Lund, Sweden.

Appleyard, D., Gerson M.S. & Lintell, M., 1976, *Livable Urban Streets: Managing Auto Traffic in Neighborhoods*, Department of Transport, Federal Highway Administration, Washington.

Archer, J., Fotheringham, N., Symmons, M. & Corben, B., 2008, *The Impact of Lowered Speed Limits in Urban and Metropolitan Areas*, MUARC Report No. 276, Monash University Accident Research Centre.

ATSB, 2004, *Road Safety in Australia: A Publication Commemorating World Health Day 2004*, Australian Transport Safety Bureau (ATSB), Canberra.

Austroads 2003, *Guide to the Selection of Road Surfacings*, AP-G63/03, Austroads, Sydney, NSW.

Austroads, 2008, *Guide to Traffic Management: Part 8: Local Area Traffic Management*, Austroads, Sydney.

Ballard, A.J., 1998, *Speed Hump Effectiveness and Public Acceptance,* Compendium of Papers for the 68th Annual Meeting of Institute for Transportation Engineers, Institute of Transportation Engineers.

Barbosa, H.M., Tight, M.R. & May, A.D., 2000, *A Model of Speed Profiles for Traffic Calmed Roads*, Transportation Research: Part A, Vol. 34, No. 2, pp. 103-123.

Berglund, B., Lindvall, T. & Schwela, D.H., 1999, *Guidelines for Community Noise*, World Health Organization, Geneva.

Besseling, H. & van Boxtel, A., 2001, *Intelligent Speed Adaptation: Results of the Dutch ISA Trial – Summary*, Transport Research Centre, Ministry of Transport, Public Works and Water Management, The Netherlands.

Biding, T. & Lind, G., 2002, *Intelligent Speed Adaptation (ISA): Results of Large-Scale Trials in Borlange, Lidkoping, Lund and Umea During the Period 1999–2002*, Publication 2002:89E, Swedish National Road Administration, Borlange, Sweden.

Bolt, R.H., Lukasik, S.J., Nolle, A.W. & Frost, A.D. (eds), 1952, *Handbook of Acoustic Noise Control – Volume 1: Physical Acoustics*, WADC Technical Report 52-204, Wright Air Development Center, Air Research and Development Command, United States Air Force, Ohio.

Boulter, P.G. & Hickman, A.J., 2001, *The Impacts of Traffic Calming Measures on Vehicle Exhaust Emissions*, TRL Report No. 483, Transport Research Laboratory, United Kingdom.

Boulter, P.G. & Webster, D.C., 1997, *Traffic Calming and Vehicle Emissions: A Literature Review*, TRL Report No. 307, Transport Research Laboratory, United Kingdom.

Brindle, R., 1992, *Local Street Speed Management in Australia – Is It Traffic Calming?*, Accident Analysis & Prevention, Vol. 24, No. 1, pp. 29-38.

Brindle, R., 1995, *Living With Traffic: Twenty-Seven Contributions to the Art and Practice of Traffic Calming 1979 – 1992*, ARRB Transport Research Ltd., Victoria.

Brindle, R., 1999, *Towards Guidelines for LATM in Different Speed Environments*, Road & Transport Research, Vol. 8, No. 1, pp. 92-95.

Brindle, R., 2005, *Speed-based Design of Traffic Calming Schemes*, Institute of Transportation Engineers (ITE) Annual Meeting, ITE, Melbourne, Australia.

Brindle, R. & Lydon, M., 1998, *Speed Control Device Evaluation: Summary Report and Suggested Generalised Speed Profiles*, Contract Report CR OC6517-3 (Austroads Project NRS 9531B), ARRB Transport Research Ltd., Vermont South, Victoria.

Buchanan, C., 1963, *Traffic in Towns*, London: HMSO.

Burrington, S., & Heart, B., 1998, *City Routes, City Rights: Building Livable Neighbourhoods and Environmental Justice By Fixing Transportation*, Conservation Law Foundation, Boston.

Carsten, O., 2002, *European Research on ISA: Where Are We Now and What Remains To Be Done*, Proceedings of the International Conference on ICT Convergence (ICTC), Nagoya, Japan.

Calongne, K., 2003, *Problems Associated with Traffic Calming Devices*, National Motorists Association Database (www.motorists.com).

Chai, C., Koorey, G. & Nicholson, A., 2011, *The Effectiveness of Two-Way Street Calming Pinch-Points*, proceedings of the IPENZ Transportation Group Conference, Auckland, 27 – 30 March 2011.

Christchurch City Council, 2009, *Generic Traffic Management Plan*, City Environment Group, Christchurch City Council, Christchurch.

City of Austin, 1996, *Neighbourhood Traffic Management Techniques: Summary of Results*, City of Austin, Texas.

Coleman, M., 1996, *The Influence of Traffic Calming Devices Upon Fire Vehicle Travel Times*, City of Portland, Oregon, Office of Transportation, Portland.

CSTB, 1991, *Theoretical and Experimental Study of the Acoustic Propagation*, Revue d'Acoustique, No.70, Centre Scientifique et Technique du Batiment (CSTB).

De Pelsmacker, P. & Janssens, W., 2007, *The Effect of Norms, Attitudes and Habits on Speeding Behaviour: Scale Development and Model Building and Estimation*, Accident Analysis and Prevention, Vol. 39, pp. 6-15.

Department for Transport, 1988, *Calculation of Road Traffic Noise*, Department for Transport, Welsh Office, London: Her Majesty's Stationary Office.

Department for Transport, 2011, *Local Transport Note 1/11: Shared Space*, Department for Transport, London.

DETR, 1997, *Cyclists at Road Narrowings*, Traffic Advisory Leaflet 01/97, Department of the Environment, Transport and the Regions, United Kingdom.

Dravitzki, V. & Kvatch, I., 2007, *Road Surface Effects on Traffic Noise: Stage 3 – Selected Bituminous Mixes*, Research Report 326, Land Transport New Zealand, Wellington.

Elvik, R., 2009, *The Power Model of the Relationship between Speed and Road Safety: Update and New Analyses*, TOI Report 1034/2009, Institute of Transport Economics, Oslo, Norway.

Elvik, R., Christensen, P. & Admunsen, A., 2004, *Speed and Road Accidents: An Evaluation of the Power Model*, TOI Report 740/2004, Institute of Transport Economics, Oslo, Norway.

Elvik, R. & Vaa, T., 2004, *Handbook of Road Safety Measures*, Elsevier Science, Oxford.

Engel, U. & Thomsen, L.K., 1992, *Safety Effects of Speed Reducing Measures in Danish Residential Areas*, Accident Analysis & Prevention, Vol. 24, No. 1, pp. 17-28.

Engwicht, D., 1992, *Reclaiming Our Cities and Towns: Better Living with Less Traffic*, New Society Publishers, Philadelphia.

Ewing, R., 1999, *Traffic Calming: State of the Practice*, Institute of Transportation Engineers, Washington, D.C.

Ewing, R. & Brown, S.J., 2009, *U.S. Traffic Calming Manual*, American Planning Association / ASCE Press, Chicago / Reston.

Du, J., Ivan J.N., Garder, P.E., & Aultman-Hall, L., 2003, Public Perceptions of Traffic Calming Device Installation," Institute of Transportation Engineers Annual Meeting and Exhibition.

Fagotti, C. & Poggi, A., 1995, *Traffic Noise Abatement Strategies: The Analysis of Real Case Not Really Effective*, in proceedings of 18th International Congress for Noise Abatement, pp. 223-233, Bologna, Italy.

FHWA, 1980, *Highway Traffic Noise*, Report No. HEV-21/8-80(20M), Federal Highway Administration, US Department of Transportation, Washington, D.C.

FHWA, 2000, *Speeding Counts on All Roads*, FHWA Office of Safety, Federal Highway Administration, US Department of Transportation, Washington, D.C.

Fildes, B.N. & Jarvis, J.R., 1994, *Perceptual Countermeasures: Literature Review*, Research Report CR4/94, Road and Traffic Authority of New South Wales, Rosebury, Australia.

Finch, D.J., Kompfner, P., Lockwood, C.R. & Maycock, G., 1994, *Speed, Speed Limits and Accidents*, Project Report No. 58, Transport Research Laboratory, Berkshire.

Fitzpatrick, K., Carlson, P., Brewer, M. & Wooldrigde, M., 2000, *Design Factors That Affect Speed on Suburban Streets*, Transportation Research Record 1751, Paper No. 01-2163, pp. 18-25.

Galloway, W.J., Clark, W.E, & Kerrick, J.S., 1969, *Urban Highway Noise: Measurement, Simulation and Mixed Reactions*, NHCRP Report 78,

Goos, J., 1986, *Experimental Projects Fkaechenhafte Traffic Calming in the Dutch Municipalities of Eindhoven and Rijswijk: Impact on Road Safety*, International Transport, Vol. 38, No. 4, 1986, pp. 278-285.

Griffiths, I.D., & Langdon, F.J., 1968, *Subjective Response to Road Traffic Noise*, Sound and Vibration, Vol. 8, No. 1, pp. 16-32.

Harper, B.C.S., 1970, *Design of the Local Street System*, Special Report No. 5, Transport Section, Department of Civil Engineering, University of Melbourne.

Highways Agency, 2011, *Design Manual for Road and Bridges*, Environmental Impact Assessment, Volume 11, Section 3, Part 7, Highways Agency, Surrey.

Hoareau, E. & Newstead, S., 2004, *An Evaluation of the Default 50 km/h Speed Limit in Western Australia*, MUARC Report No. 230, Monash University Accident Research Centre, Victoria.

Hoareau, E., Newstead, S. & Cameron, M., 2006, *An Evaluation of the Default 50 km/h Speed Limit in Victoria,* MUARC Report No. 261, Monash University Accident Research Centre, Victoria.

Homburger, W.S., Hall, J.W., Reilly, W.R. & Sullivan, E.C., 2001, *Fundamentals of Traffic Engineering*, 15th ed., Institute of Transportation Studies, University of California, Berkeley.

Horberry, T., Hartley, L., Gobetti, K., Walker, F., Johnson, B., Gersbach, S. & Ludlow, J., 2004, *Speed Choice by Drivers: The Issue of Driving Too Slowly*, Ergonomics, Vol. 47, pp. 1561-1570.

Huzevka, P., 2005, *Traffic Management in Sweden's Neighbourhoods: Examples from Gothenburg*, Institute of Transportation Engineers Annual Meeting and Exhibit of Compendium Technical Papers, 7–10 August 2005, Melbourne, Australia.

ISO, 1997, *Acoustics – Measurement of the Influence of Road Surfaces on Traffic Noise – Part 1: Statistical Pass-By Method*, ISO 11819-1:1997, International Organisation for Standardisation, Geneva.

ITE, 1997, *Guidelines for the Design and Application of Speed Humps*, Institute Of Transportation Engineers (ITE), Washington, DC.

ITE, 2007, *Guidelines for the Design and Application of Speed Humps*, Institute of Transportation Engineers (ITE), Washington, DC.

Jamson, S., Carsten, O., Chorlton, K. & Fowkes, M., 2006, *Intelligent Speed Adaptation: Literature Review and Scoping Study*, The University of Leeds and MIRA Ltd.

Johnson, D.R. & Saunders, E.G., 1968, *The Evaluation of Noise from Freely Flowing Road Traffic*, Sound and Vibration, Vol. 7, No. 2, pp. 287-309.

Johnson, L. & Nedzesky, A.J., 2004, *A Comparative Study of Speed Humps, Speed Slots and Speed Cushions,* ITE Annual Meeting Compendium, Institute of Transportation Engineers (ITE), Washington, D.C.

Jonah, B.A., Thiessen, R. & Au-Yeung, E., 2001, *Sensation Seeking, Risky Driving and Behavioural Adaptation*, Accident Analysis and Prevention, Vol. 33, pp. 679-684.

Jorgensen, F. & Polak, J., 1993, *The Effect of Personal Characteristics on Driver's Speed Selection: An Economic Approach*, Transport Economics and Policy, Vol. 27, No. 3, pp. 237-252.

Josse, R., *Notions d'acoustique à l'usage des ingénieurs architectes et urbanistes*, Eyrolles, Paris.

Jurewicz, C., 2009, *Impact of LATM Treatments on Speed and Safety*, Road & Transport Research, Volume 18, No.4, pp. 14-22.

Kjemtrup, K. & Herrstedt, L., 1992, *Speed Management and Traffic Calming in Urban Areas in Europe: A Historical View*, Accident Analysis & Prevention, Vol. 24, No. 1, pp 57 -65.

Kloeden, C.N., McLean, A.J. & Glonek, G., 2002, *Reanalysis of Travelling Speed and the Risk of Crash Involvement in Adelaide South Australia*, CR 207, Australian Road Safety Bureau, Canberra, pp. 3-6.

Kloeden, C.N., McLean A.J., Moore, V.M. & Ponte, G., 1998, *Travelling Speed and the Risk of Crash Involvement*, National Health and Medical Research Council (NHMRC) Road Accident Research Centre, University of Adelaide, Adelaide.

Kloeden, C., Woolley, J., & McLean, J., 2004, *Evaluation of the South Australian Default 50 km/h Speed Limit,* CASR Report No. 5, Centre for Automotive Safety Research, University of Adelaide, Adelaide.

Kokowski, P. & Makarewicz, R., 1997, *Interrupted Traffic Noise*, Acoustical Society of America, Vol. 101, No. 1, pp. 360-371.

Kokowski, P. & Makarewicz, R., 2006, *Predicted Effects of a Speed Bump on Light Vehicle Noise*, Applied Acoustics, Vol. 67, No. 6, pp. 570-579.

Lahrmann, H., Madsen, J.R. & Borocj, T., 2001, *Intelligent Speed Adaptation – Development of a GPS-based ISA Systems an Field Trial of the Systems with 24 Test Drivers,* Proceedings of the 8th World Congress on Intelligent Transport Systems, Sydney, Australia.

Lelong, J. & Michelet, R., 1999, *Effect of Acceleration on Vehicle Noise Emission*, Proceedings of Forum Acustica (Joint ASA/EAA Meeting), Berlin, Germany.

Lennard, S.H. & Lennard, H.L., 1995, *Livable Cities Observed*, Gondolier Press.

Litman, T., 1999, *Traffic Calming Benefits, Costs and Equity Impacts*, Victoria Transport Policy Institute, Victoria.

Lockwood, I.M., 1997, *ITE Traffic Calming Definition*, Institute of Transportation Engineers, Volume 67, pp 22-24.

Lynch, K. & Hack, G, 1984, *Site Planning*, 3rd ed., MIT Press, Cambridge, MA.

Mao, J. and Koorey, G., 2010, *Investigating and Modelling the Effects of Traffic Calming Devices*, Christchurch, New Zealand: IPENZ Transportation Group Conference 2010, 14-17 March 2010.

Marek, J.C. & Walgren, S., 1998, *Mid-block Speed Control: Chicanes and Speed Humps*, Compendium of Papers for the 68th Annual Meeting of Institute for Transportation Engineers, Institute for Transportation Engineers.

Marret, J.L., 1994, *In speed … or In Security? Elements of Understanding and Tracks of Reflection,* Research Report), Société de l'assurance automobile du Québec, Québec, p.p. 140.

Martens, M., Comte, S., and Kaptein, N., 1997, *The Effects of Road Design on Speed Behaviour: A Literature Review*, VTT, Finland.

Ministry of Transport, France, 2001, *Guide to Good Driving*, Directorate of Road Safety & Traffic Management, Ministry of Transport, Paris.

Ministry of Transport, New Zealand, 2011a, *Speeding: Crash Factsheet 2011*, Ministry of Transport, Wellington.

Ministry of Transport, New Zealand, 2011b, *2011 Speed Survey: Results Summary*, Ministry of Transport, Wellington.

Ministry of Transport, New Zealand, 2011c, *The New Zealand Vehicle Fleet: Annual Fleet Statistics 2010*, Statistical Report, Ministry of Transport, Wellington.

Minnema, R., 2006, *The Evaluation of the Effectiveness of Traffic Calming Devices in Reducing Speeds on Local Urban Roads in New Zealand*, Master Thesis, Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch.

Mitchell, P., 2009, *Speed and Road Traffic Noise*, UK Noise Association, Chatham, Kent.

Montgomery County Fire and Rescue Commission, 1997, *The Effects of Speed Humps and Traffic Circles On Responding Fire-Rescue Apparatus in Montgomery County, Maryland*, Maryland Technology Transfer Centre.

MORI, 2001, *Drivers Undecided Over Speed Limiters In Cars*, Ipsos MORI, London.

MORI, 2002, *Motorists Welcome Speed Warning Devices As Way To Reduce Road Injuries*, Ipsos MORI, London.

MRWA, 1990, *Guidelines for Local Area Traffic Management,* Pak-Poy and Kneebone Pty. Ltd. and Main Roads Department Western Australia (MRWA), Perth.

MRWA, 2011, *Guidelines for Local Area Traffic Management,* (D08#102211), Main Roads Department Western Australia (MRWA), Perth.

Nilsson, G., 1982, *The Effects of Speed Limits on Traffic Crashes in Sweden*, International Symposium on the Effects of Speed Limits on Traffic Crashes and Fuel Consumption 1982, Dublin, Organisation for Economy, Cooperation and Development (OECD), Paris, pp. 1-8.

Nilsson, G., 2004, *Traffic Safety Dimensions and the Power Model to Describe the Effect of Speed on Safety*, Lund Institute of Technology, Lund.

NIST / SEMATECH, 2003-2012, *e-Handbook of Engineering Statistics*, National Institute of Standards and Technology / SEMATECH, Gaithersburg, MD. (http://www.itl.nist.gov/div898/handbook/index.htm)

NZS 6801:2008, *Acoustics – Measurement of Environmental Sound*, Standards New Zealand, Wellington.

OECD/ECMT, 2006, *Speed Management*, Joint Transport Research Centre of the Organisation for Economic Cooperation and Development (OECD) and the European Conference of Ministers of Transport (ECMT), Paris.

Paatalo, M., Peltola, H. & Kaliiop, M., 2001, *Intelligent Speed Adaptation – Effects on Driving Behaviour*, Proceedings of the Conference on Traffic Safety on Three Contitents, Moscow, Russia.

Palisade, 2010, *Guide to Using @RISK – Risk Analysis and Simulation Add-In for Microsoft Excel, Version 5.7*, Palisade Corporation, New York.

Pamanikabud, P. & Tharasawatpipat, C., 1999, *Modelling of Urban Area Stop-and-Go Traffic Noise*, Transportation Engineering, Vol. 125, pp. 152-159.

Patterson, T.L., Frith, W.J., & Small, M.W., 2000, *Down with Speed: A Review of the Literature, and the Impact of Speed on New Zealanders*, Accident Compensation Corporation (ACC) and Land Transport Safety Authority (LTSA), Wellington.

Pharoah, T., 1992, *Traffic Calming Guidelines*, Devon County Council, Exeter.

Pharoah, T. & Russell, J., 1989, *Traffic Calming: Policy and Evaluations in Three European Countries*, Occasional Paper 2/1989, Department of Planning, Housing and Development, South Bank Polytechnic, London.

Ponnaluri, R.V. & Groce, P.W., 2005, *Operational Effectiveness of Speed Humps in Traffic Calming*, Institute of Transportation Engineers (ITE) Journal, Vol. 75, No. 7, pp. 26-30.

Quartieri, J., Mastorakis, N.E., Iannone, G., Guarnaccia, C., D'Ambrosio, S., Troisi, A. & Lenza, T.L.L., *A Review of Traffic Noise Predictive Models*, in proceedings of the 5th WSEAS International Conference on "Applied and Theoretical Mechanics", Canary Islands, Spain, 14-16 December 2009, pp. 72-80.

Ratkowsky, D.A., 1990, *Handbook of Nonlinear Regression Models*, Marcel Dekker Inc., New York.

RLS, 1990, *Richtlinien für den Lärmschutz an Straßen*, BM dür Verkehr, Bonn.

Rosen, E. & Sander, U., 2009, *Pedestrian Fatality Risk as a Function of Car Impact Speed*, Accident Analysis and Prevention, Vol. 41, No. 3, pp. 536-542.

RoSPA, 1996, *Road Safety Information: Speed and Road Accidents*, Royal Society for the Prevention of Accidents (RoSPA), Birmingham.

Sergerie, D., 2008, *Road Speed: Health Impact and Counteractive Measures – Scientific Review*, Institut national dé sante publique du Québec, Gouvernement du Québec.

Shinar, D., 2007, *Traffic Safety and Human Behaviour*, Elsevier, Amsterdam.

Shinar, D., Schechtman, E. & Compton, R.P., 2001, *Self-reports of Safe Driving Behaviours in Relationship to Sex, Age, Education and Income in the US Adult Driving Population*, Accident Analysis and Prevention, Vol. 33, pp. 111-116.

Smith, D., Hallmark, S., Knapp, K. & Thomas, G., 2002, *Temporary Speed Hump Impact Evaluation*, CTRE Project 00-73, Center for Transportation Research and Education, Iowa State University, Iowa.

Snedecor, G.W. & Cochran, W.G, 1989, *Statistical Methods*, 8th ed., Iowa State University Press, Ames, Iowa.

Standards NZ, *Acoustics – Road-traffic Noise – New and Altered Roads NZS 6806:2010*, Standards New Zealand, Wellington.

Stillings, T. & Lockwood, I., 2001, *West Palm Beach Traffic Calming: The Second Generation*, City of West Palm Beach Transportation Division, Florida.

SWOV, 2006, *Advancing Sustainability Safety: National Safety Outlook for 2005 – 2020*, SWOV Institute for Road Safety Research, Leidschendam.

SWOV, 2010, *Speed Choice: The Influence of Man, Vehicle and Road*, SWOV Factsheet, SWOV Institute for Road Safety Research, Leidschendam.

T & E, 2001, *Lower Urban Speed Limits Factsheet*, European Federation for Transport & Environment (T & E), Brussels.

Taylor, M.A.P., 1986, *Controlling Vehicle Speeds on Local Streets*, Technical Note No.1, Australian Road Research, Vol.16, No.1, pp. 42-44.

Taylor, M.C., Lynam, D.A. & Baruya, A., 2000, *The Effect of Drivers' Speed on the Frequency of Road* Accidents, TRL Report 421, Transport Research Laboratory, Crowthorne, Berkshire.

Transportation Research Board (TRB), 1998, *Managing Speed: A Review of Current Practice for Setting and Enforcing Speed Limits*, Special Report 254, Transportation Research Board (TRB), National Academy Press, Washington, DC.

Tranter, P.J. & Doyle, J.W., 1996, *Reclaiming the Residential Street as Play Space*, International Play, Vol. 4, pp. 91-97.

Verhalyi, A. & Makinen, T., 2001, *The Effects of In-Car Speed Limiters: Field Studies*, Transportation Research Part C: Emerging Technologies, No. 9, pp. 191 – 211.

Walsh, D. & Smith, M., 1999, *Effective Speed Management the Next Step Forward: Saving Lives by Decreasing Speeds in Local Streets*, Proceedings of the Research, Policing and Education Road Safety Conference, Canberra, Volume 2, pp. 685-694.

Webster, D.C., 1993, *Road Humps for Controlling Vehicle Speeds*, Project Report 18, Transport Research Laboratory, Crowthorne, Berkshire.

Webster, D. & Mackie, A, 1996, *Review of Traffic Calming Schemes in 20 mph zones,* TRL Report No. 215, Transportation Research Laboratory, Crowthorne, Berkshire.

WHO, 2004, *World Report on Road Traffic Injury Prevention*, World Health Organisation, Geneva.

WHO, 2011, *Burden of Disease from Environmental Noise: Quantification of Healthy Life Years Lost in Europe,* World Health Organisation Regional Office for Europe, Copenhagen.

Yamamoto, K., 2010, *Road Traffic Noise Prediction Model "ASJ RTN-Model 2008": Report of the Research Committee on Road Traffic Noise'*, Acoustics Science & Technology, Vol. 31, No. 1, pp. 2-55.

Zeeger, C., Seiderman, C., Lagerwey, P., Cynecki, M., Ronkin, M., & Schneider, R., 2002, *Pedestrian Facilities User Guide: Providing Safety and Mobility*, Publication FHWA-RD-01-102, Federal Highway Administration, Washington, D.C.

Zein, S.R., Geddes, E., Hemsing, S. & Johnson, M., 1997, *Safety Benefits of Traffic Calming*, Transportation Research Record No. 1578, pp. 3-10.

Appendix A

A-1 STREET VIEWS OF RANDOLPH STREET, WOOLSTON

A-2 STREET VIEWS OF MACKENZIE AVENUE, WOOLSTON

A-3 STREET VIEWS OF RATTRAY STREET, RICCARTON

A-4 STREET VIEWS OF STRATFORD STREET, FENDALTON

A-5 STREET VIEWS OF KIRKWOOD AVENUE, ILAM

A-6 STREET VIEWS OF HAMILTON AVENUE, ILAM

A-7 STREET VIEWS OF SNOWDON ROAD, FENDALTON

A-8 STREET VIEWS OF ST ASAPH STREET, PHILLIPSTOWN

A-9 STREET VIEW OF QUINNS ROAD, SHIRLEY

A-10 STREET VIEWS OF BROCKWORTH PLACE, RICCARTON

A-11 STREET VIEWS OF REYNOLDS AVENUE, BISHOPDALE

A-12 STREET VIEWS OF WATTLE DRIVE, NEW BRIGHTON

A-13 STREET VIEWS OF KINGS STREET, SYDENHAM

A-14 STREET VIEWS OF DEVON STREET, ADDINGTON

A-15 STREET VIEWS OF TANKERVILLE STREET, HOON HAY

A-16 STREET VIEWS OF AYLESFORD STREET, MAIREHAU

A-17 STREET VIEWS OF FRANCIS AVENUE, MAIREHAU

A-18 STREET VIEWS OF STUDHOLME STREET, SOMERFIELD

A-19 STREET VIEWS OF GARDEN ROAD, FENDALTON

A-20 STREET VIEWS OF JOY STREET, SHIRLEY

Appendix B

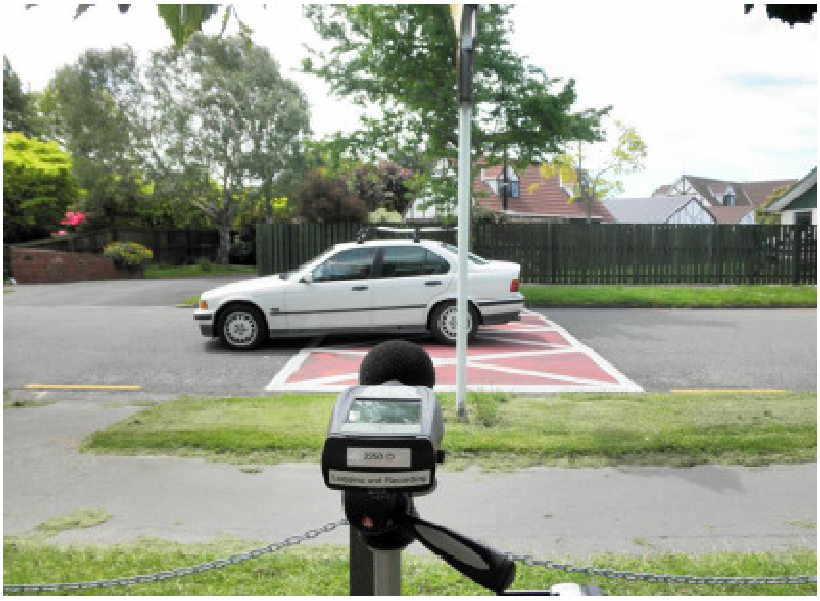
DESCRIPTION OF TRAFFIC CALMING TREATMENTS FOR STREETS IN THE RANDOM STUDY

No.	Road	Construction Year	'Before' period	'After' period	Treatment
1	Aylesford Street	2006-2007	2003-2005	2008-2010	Tables (5 no.s)
2	Francis Avenue	2006-2007	2003-2005	2008-2010	Tables (3 no.s)
3	Stratford Street	2004	1998-2003	2005-2010	Narrowing, 2-lane
4	Snowdon Road	2005	2000-2004	2006-2010	Humps (4 no.s)
5	Hamilton Avenue	2006-2007	2003-2005	2008-2010	Narrowing, 2-lane
6	Burke Street	2007	2004-2006	2008-2010	Narrowing, 2-lane
7	Rattray Street	2007-2008	2005-2006	2009-2010	Angled slowpoint, 1-lane
8	Kirkwood Avenue	2006-2007	2003-2005	2008-2010	Midblock narrowing, 1-lane
9	Randolph Street	2007	2004-2006	2008-2010	Table
10	Mackenzie Avenue	2007-2008	2005-2006	2009-2010	Angled slowpoint, 1-lane
11	Perry Street	2007	2004-2006	2008-2010	Angled slowpoint, 1-lane
12	Barbour Street	2007	2004-2006	2008-2010	Platform + Narrowing, 2-lane, Angled slowpoint 1-lane
13	Grafton Street	2007-2008	2005-2006	2009-2010	Platform + Narrowing, 2-lane, Raised junctions (2 no.s)
14	Grenville Street	2006	2002-2005	2007-2010	Angled slowpoint, 1-lane
15	Baretta Street	2006	2002-2005	2007-2010	Narrowings, 1-lane (2 no.s)
16	Carrick Street	2006-2007	2003-2005	2008-2010	Narrowings, 1-lane (3 no.s)
17	Flockton Street	2006-2007	2003-2005	2008-2010	Narrowings, 2-lane (2 no.s)

18	Fairfield Avenue	2006-2007	2003-2005	2008-2010	Narrowing 1-lane, Angled slowpoint 2-lane
19	Wherstead Road	2003-2004	1997-2002	2005-2010	Narrowings, 2-lane (2 no.s)
20	Webb Street	2004	1998-2003	2005-2010	Narrowing, 2-lane
21	Geraldine Street	2004	1998-2003	2005-2010	Narrowing, 2-lane
22	Saltaire Street	2005-2006	2001-2004	2007-2010	Table
23	Merivale Lane	2002-2003	1995-2001	2004-2010	Humps (2 no.s)
24	Mary Street	2005	2000-2004	2006-2010	Narrowing, 2-lane, Raised junction
25	Grants Road	2005	2000-2004	2006-2010	Table
26	Glenroy Street	2007	2004-2006	2008-2010	Table
27	Hastings Street	2004-2005	1999-2003	2006-2010	Hump, Roundabout, Central Islands (2 no.s)
28	Wildberry Street	2004-2005	1999-2003	2006-2010	Narrowings, 1-lane (2 no.s)

Appendix C

C-1 STREET VIEWS AND EXPERIMENTAL SETUP AT LOCHEE ROAD, UPPER RICCARTON (NEAR 75 MM SPEED HUMP)

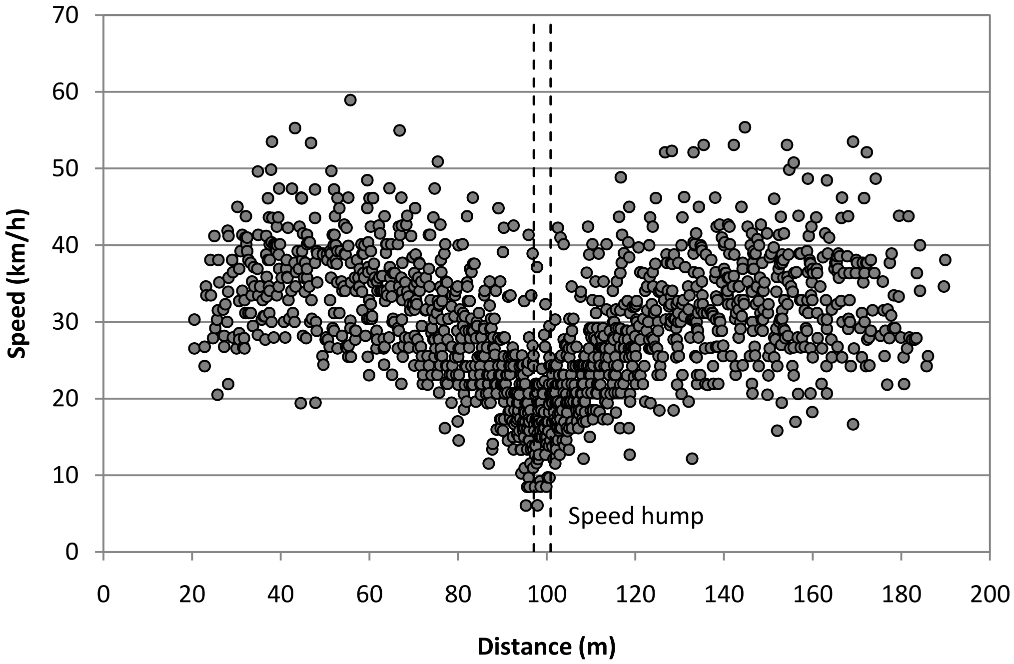


C-2 STREET VIEWS AND EXPERIMENTAL SETUP AT LOCHEE ROAD, UPPER RICCARTON (NEAR FLAT SECTION)

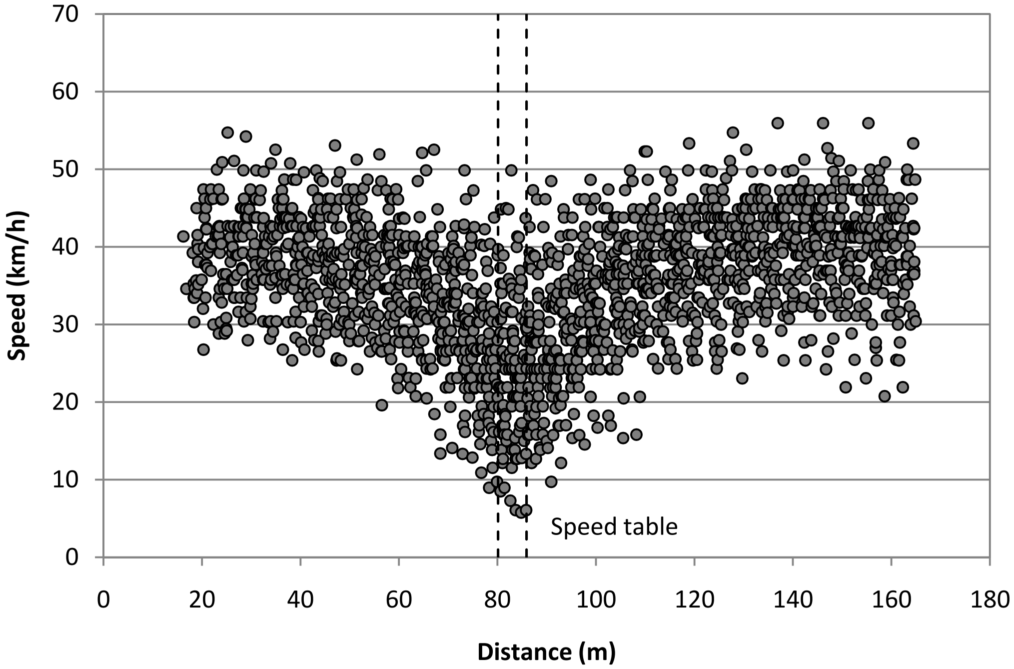
C-3 STREET VIEWS AND EXPERIMENTAL SETUP AT WADELEY ROAD, ILAM (NEAR 100 MM SPEED HUMP)

Appendix D

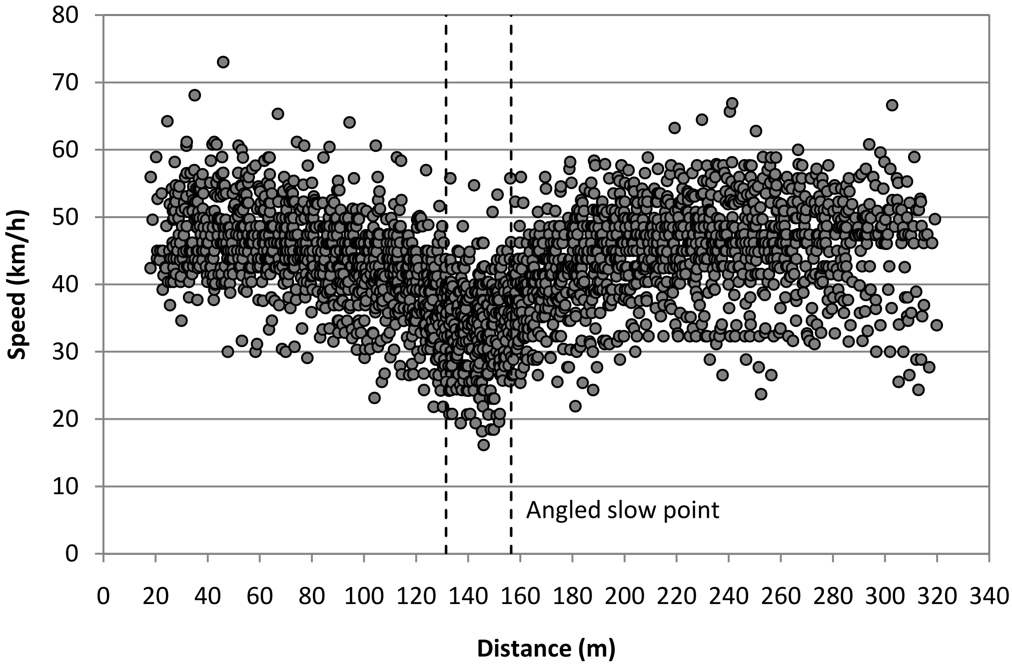
D-1 PLOT OF VEHICLE SPEEDS ON BURKE STREET, ADDINGTON



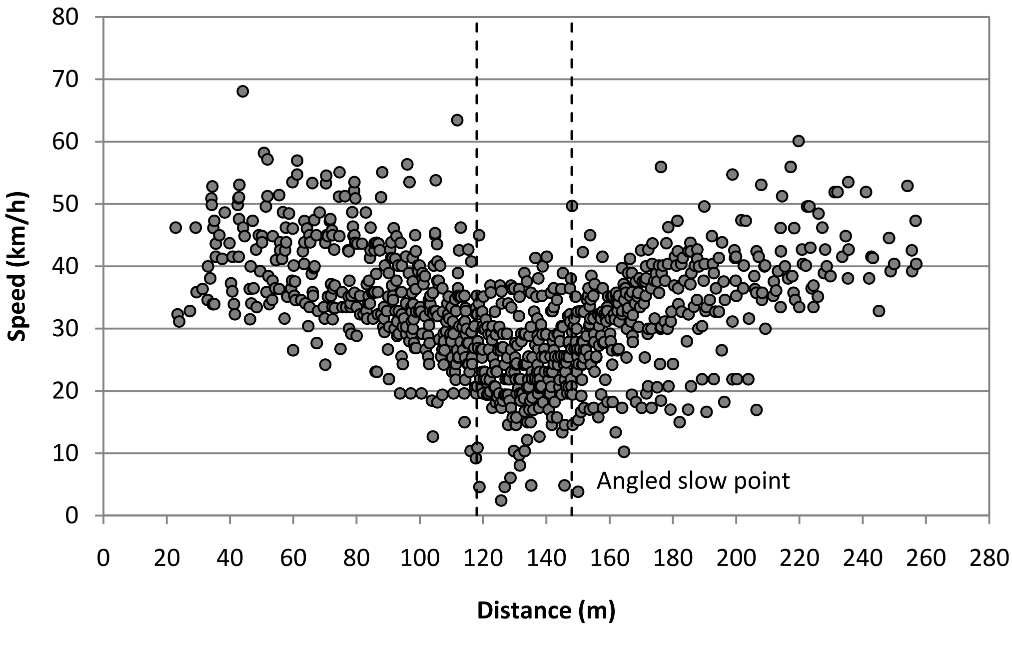
D-2 PLOT OF VEHICLE SPEEDS ON RANDOLPH STREET, WOOLSTON



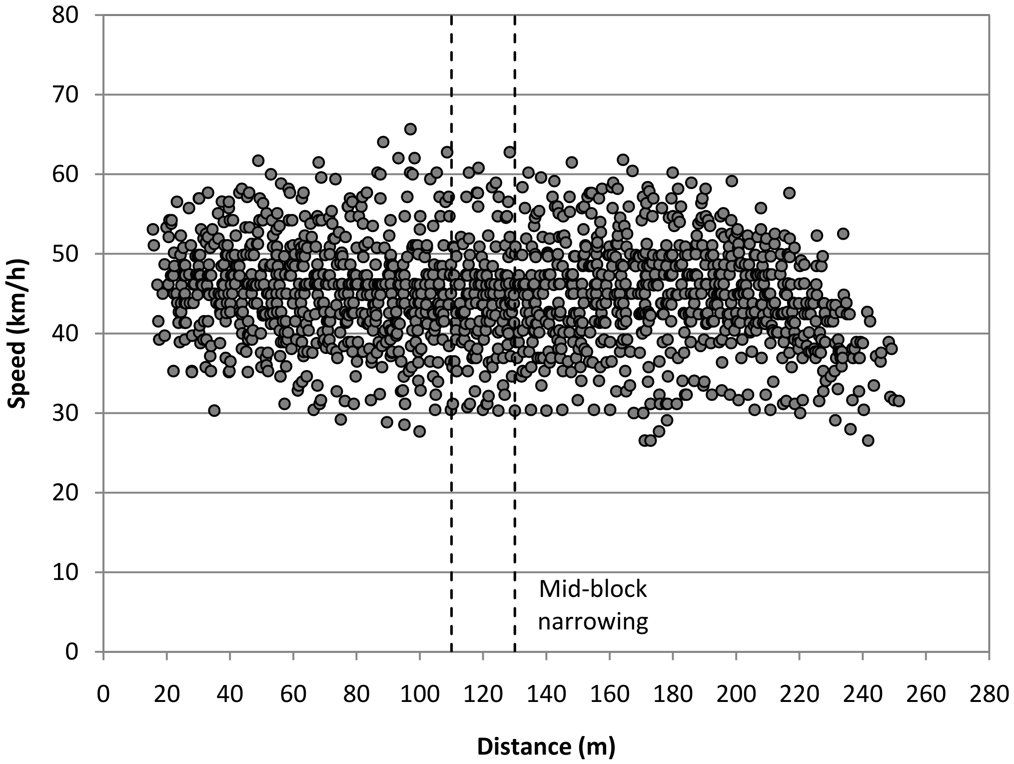
D-3 PLOT OF VEHICLE SPEEDS ON MACKENZIE AVENUE, WOOLSTON



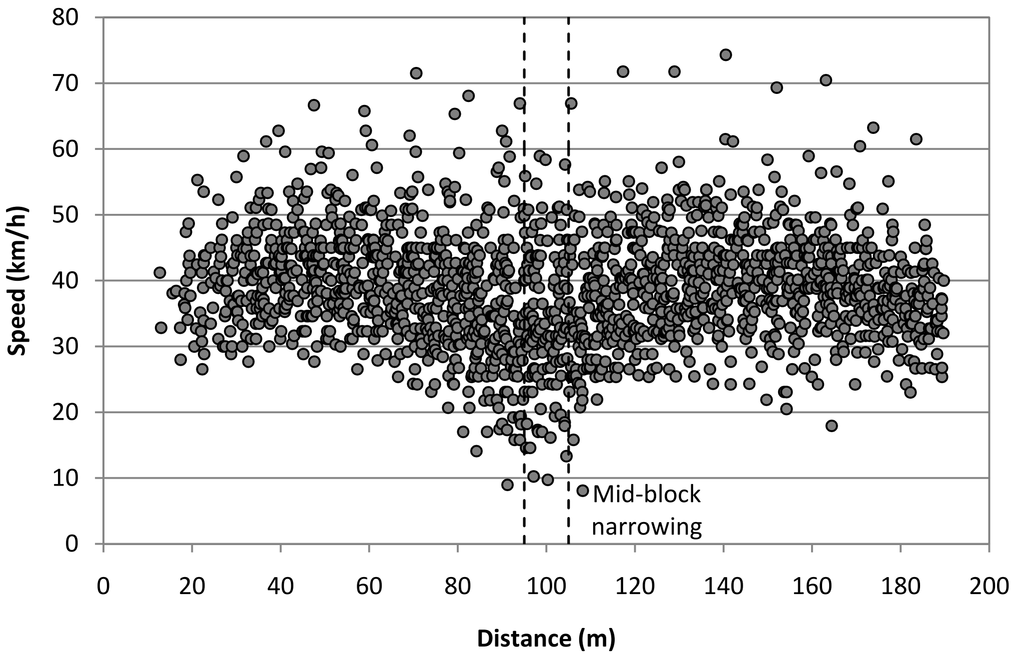
D-4 PLOT OF VEHICLE SPEEDS ON RATTRAY STREET, RICCARTON



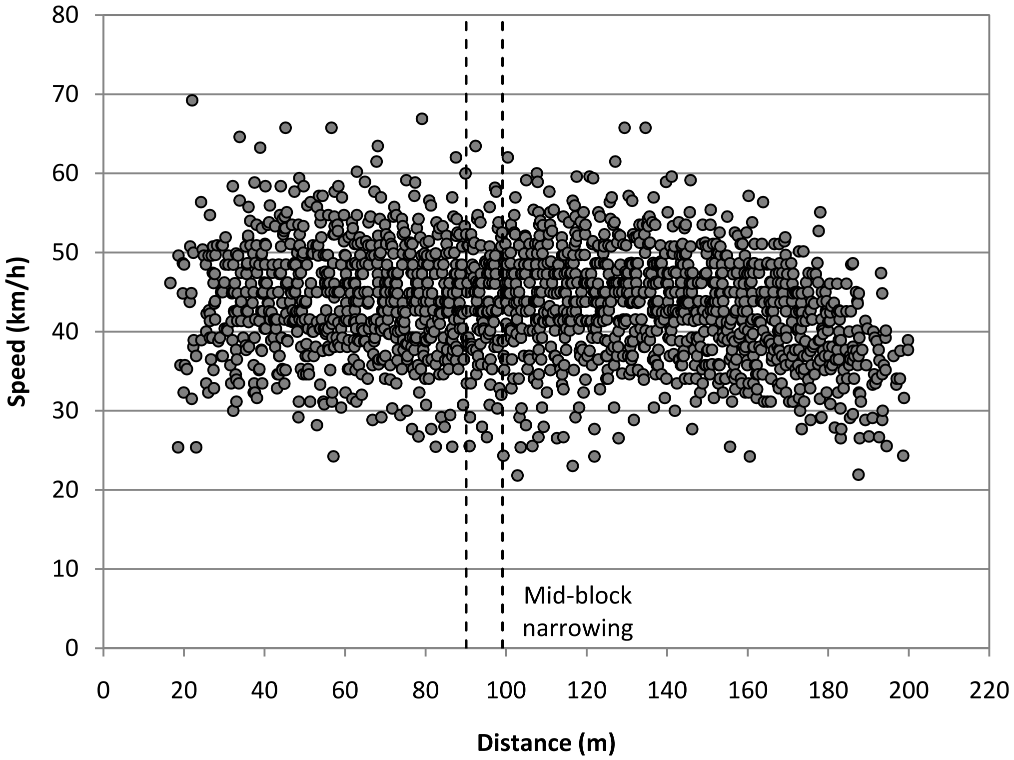
D-5 PLOT OF VEHICLE SPEEDS ON STRATFORD STREET, FENDALTON



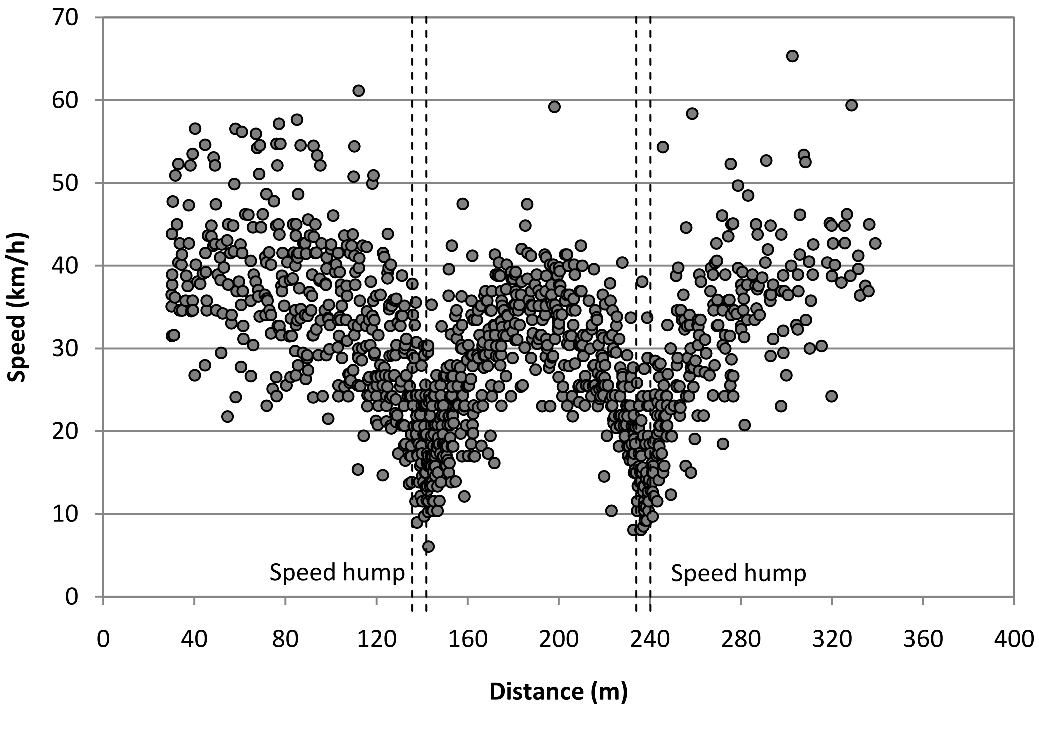
D-6 PLOT OF VEHICLE SPEEDS ON KIRKWOOD AVENUE, ILAM



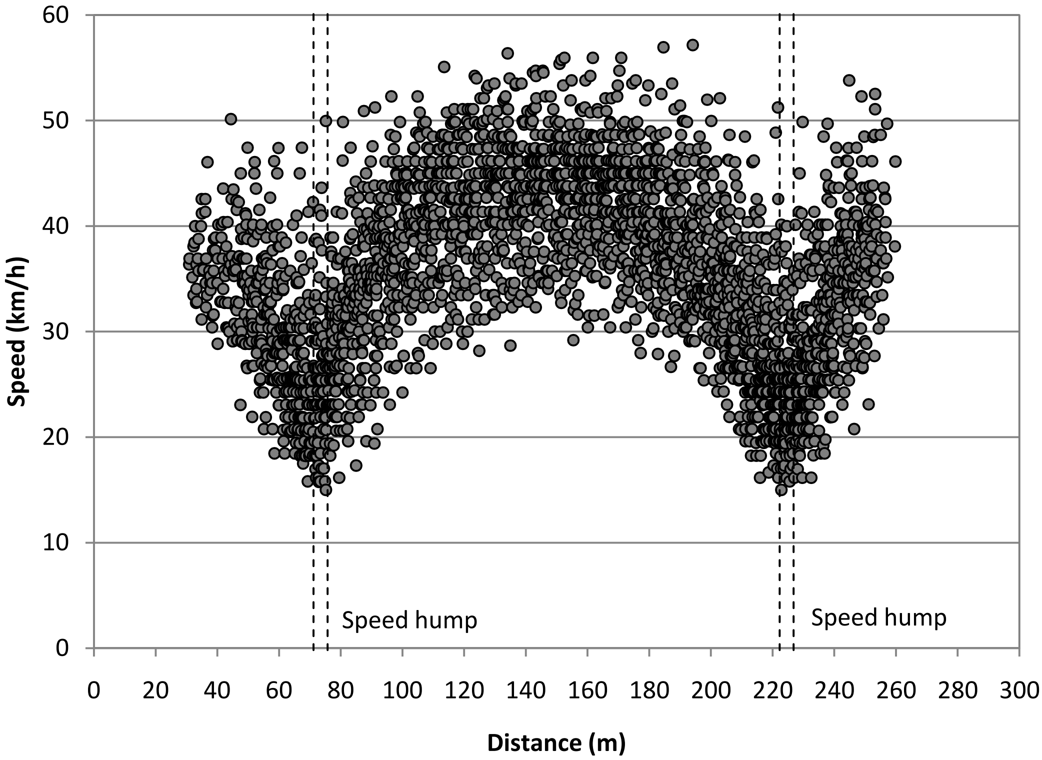
D-7 PLOT OF VEHICLE SPEEDS ON HAMILTON AVENUE, ILAM



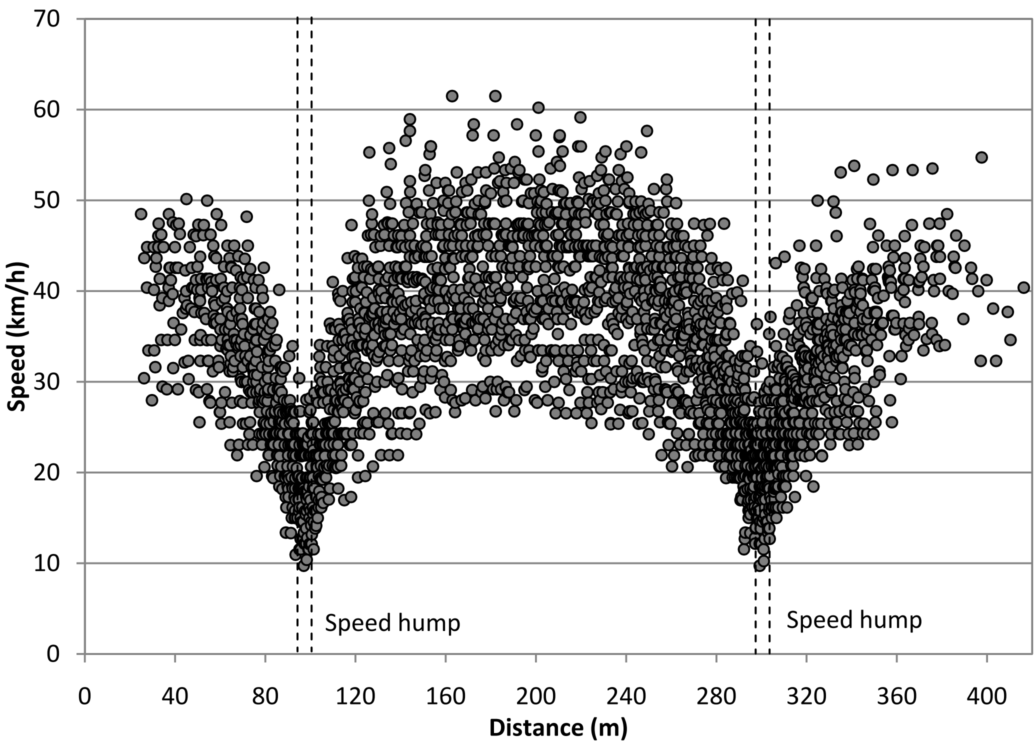
D-8 PLOT OF VEHICLE SPEEDS ON BROCKWORTH PLACE, RICCARTON



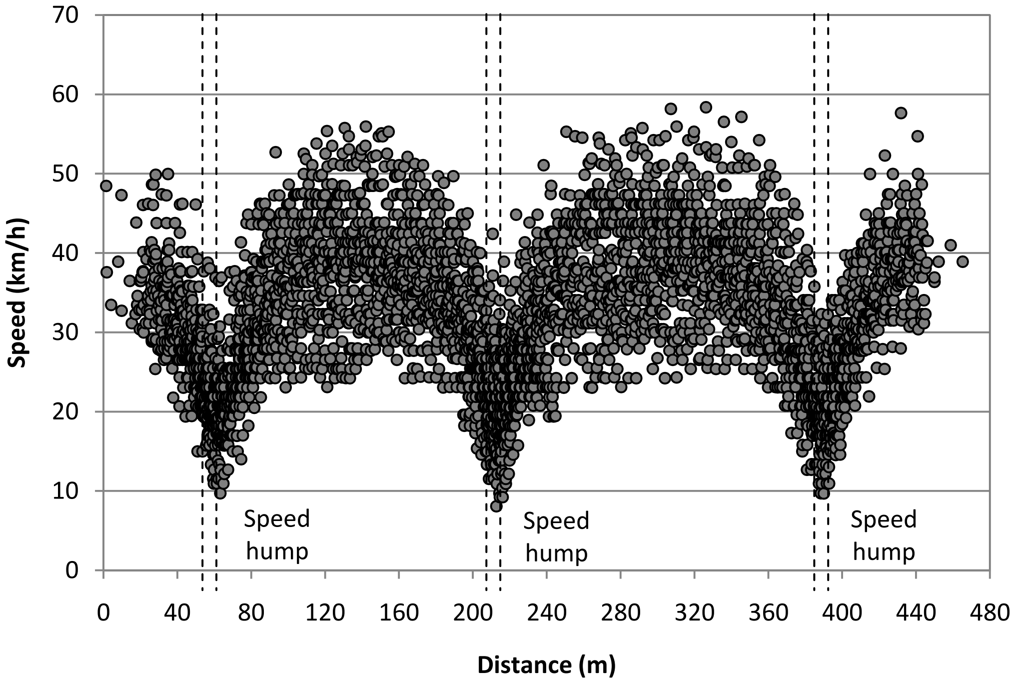
D-9 PLOT OF VEHICLE SPEEDS ON REYNOLDS AVENUE, BISHOPDALE



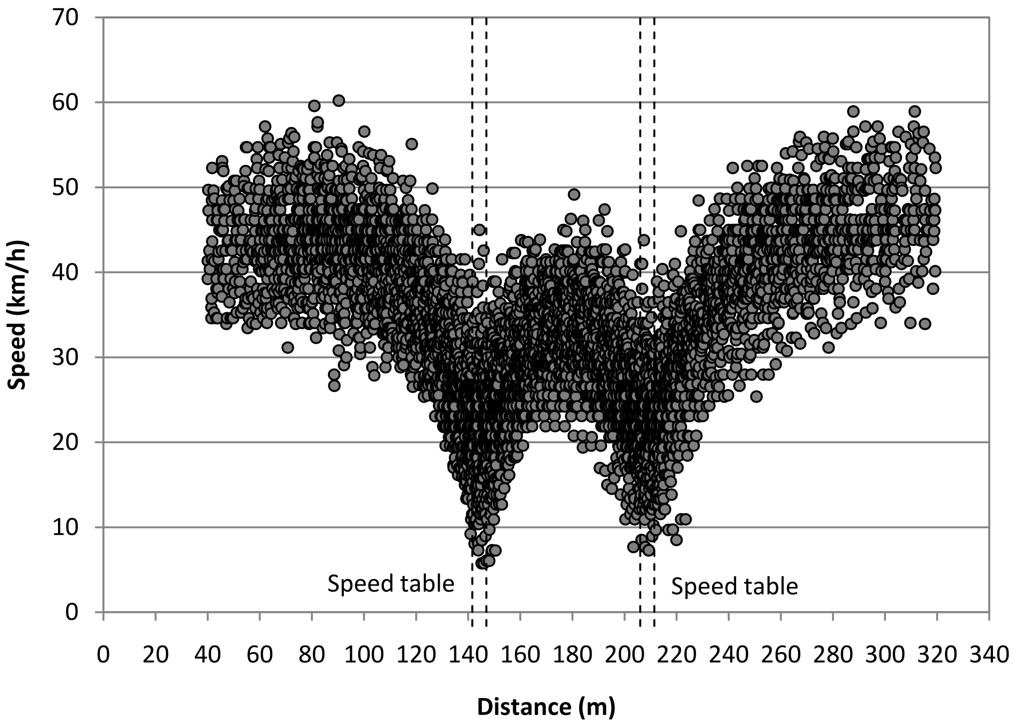
D-10 PLOT OF VEHICLE SPEEDS ON KINGS STREET, SYDENHAM



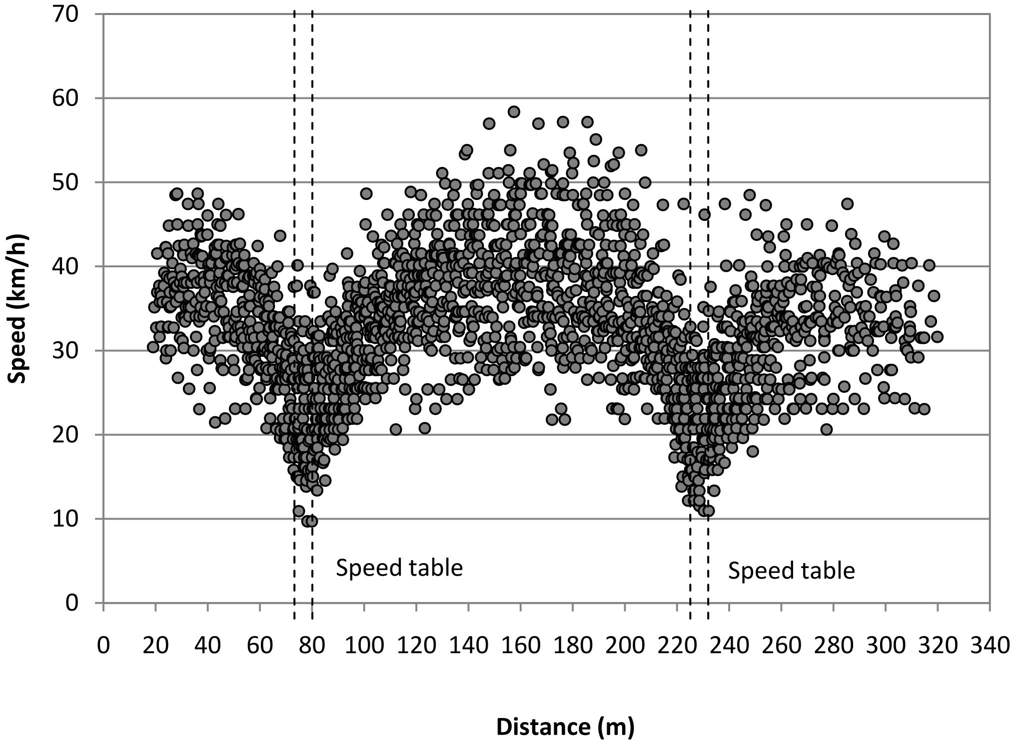
D-11 PLOT OF VEHICLE SPEEDS ON TANKERVILLE STREET, HOON HAY



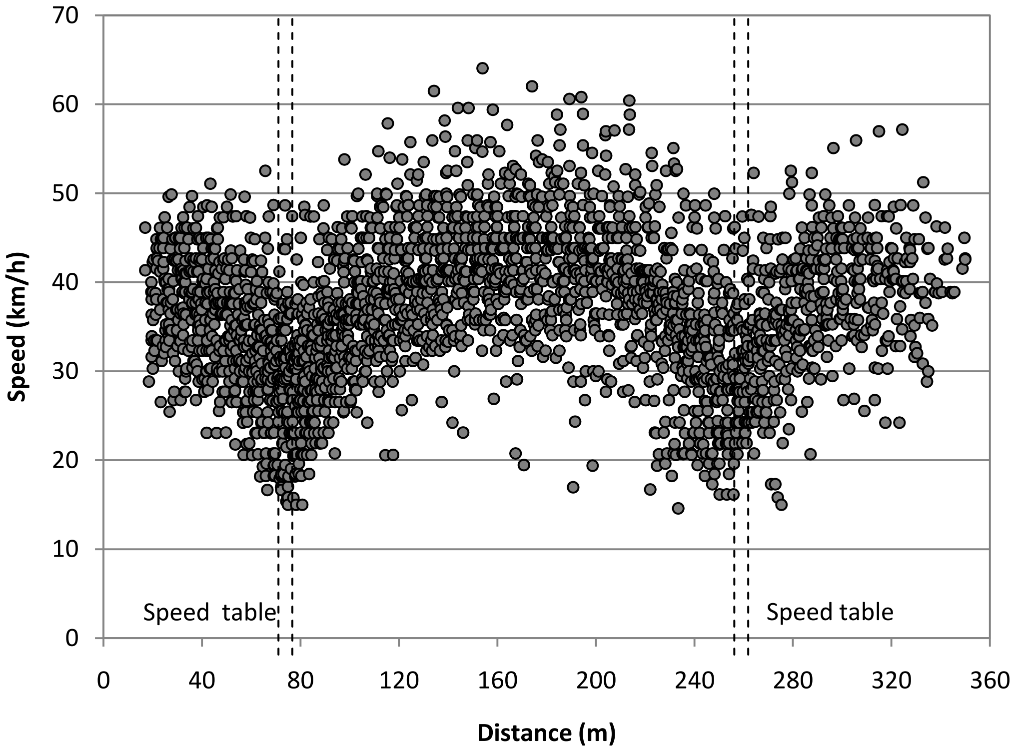
D-12 PLOT OF VEHICLE SPEEDS ON JOY STREET, SHIRLEY



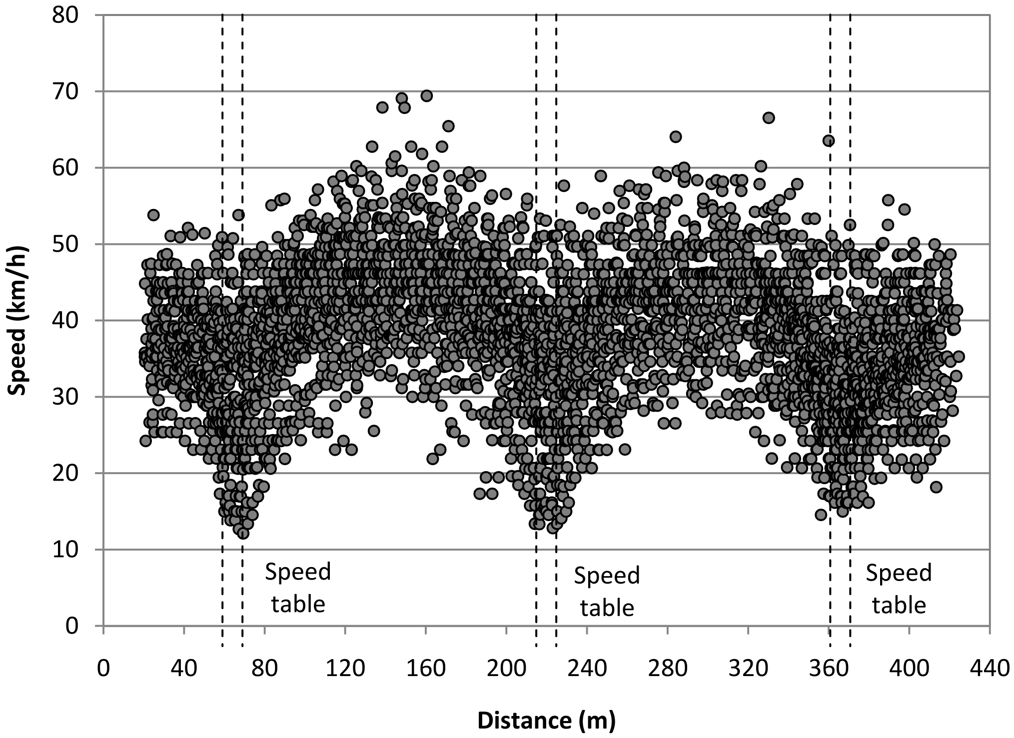
D-13 PLOT OF VEHICLE SPEEDS ON STUDHOLME STREET, SOMERFIELD



D-14 PLOT OF VEHICLE SPEEDS ON GARDEN ROAD, FENDALTON



D-15 PLOT OF VEHICLE SPEEDS ON FRANCIS AVENUE, MAIREHAU



Appendix E

E-1 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MEAN SPEEDS – SPEED HUMP ON BURKE STREET, ADDINGTON

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance at the device is smaller

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	P-value
0.5669	1.4154	0.9931

Since F <= Critical F, reject the null hypothesis.
The variance at the device is smaller.

t-Test: Two-Sample (Unequal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	At device	*At distance with highest mean*
Mean	17.56898	36.60857
Variance	28.09382	49.56035
Observations	62	135
df	154	
t Stat	-21.0226	
P(T<=t) two-tail	4.16E-47	
t Critical two-tail	1.975488	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.

E-2 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MEAN SPEEDS – SPEED TABLE ON RANDOLPH STREET, WOOLSTON

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance at the device is larger

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	P-value
2.4629	1.3456	0.0000

Since F > Critical F, reject the null hypothesis.
The variance at the device is larger.

t-Test: Two-Sample (Unequal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	At device	*At distance with highest mean*
Mean	24.52586	40.06518
Variance	91.00183	36.94883
Observations	77	224
df	98	
t Stat	-13.39	
P(T<=t) two-tail	7.31E-24	
t Critical two-tail	1.984467	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.

E-3 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MEAN SPEEDS – ANGLED SLOW POINT ON MACKENZIE AVENUE, WOOLSTON

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance at the device is larger

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	P-value
1.0092	1.2786	0.4823

Since F <= Critical F, accept the null hypothesis.
The variances are equal.

t-Test: Two-Sample (Equal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	At device	*At distance with highest mean*
Mean	33.84118	46.44839
Variance	47.13424	46.70418
Observations	311	138
Pooled Variance	47.00243	
df	447	
t Stat	-17.9786	
P(T<=t) two-tail	8.87E-55	
t Critical two-tail	1.965285	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.

E-4 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MEAN SPEEDS – ANGLED SLOW POINT ON RATTRAY STREET, RICCARTON

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance at the device is larger

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	P-value
1.3883	1.5438	0.1066

Since F <= Critical F, accept the null hypothesis.
The variances are equal.

t-Test: Two-Sample (Equal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	At device	*At distance with highest mean*
Mean	24.57875	42.66038
Variance	55.72229	40.13822
Observations	241	41
Pooled Variance	53.49599	
df	280	
t Stat	-14.6337	
P(T<=t) two-tail	2.09E-36	
t Critical two-tail	1.968472	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.

E-5 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MEAN SPEEDS – MID-BLOCK NARROWING ON STRATFORD STREET, FENDALTON

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance at the device is larger

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	P-value
1.1034	1.4474	0.3353

Since F <= Critical F, accept the null hypothesis.
The variances are equal.

t-Test: Two-Sample (Equal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	At device	*At distance with highest mean*
Mean	44.15912	46.01373
Variance	53.28863	48.58041
Observations	147	63
Pooled Variance	51.88522	
df	208	
t Stat	-1.70982	
P(T<=t) two-tail	0.088791	
t Critical two-tail	1.971435	

Since p > 0.05, accept the null hypothesis.
The means are the same.

E-6 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MEAN SPEEDS – MID-BLOCK NARROWING ON KIRKWOOD AVENUE, ILAM

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance at the device is larger

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	P-value
1.6413	1.2930	0.0008

Since F > Critical F, reject the null hypothesis.
The variance at the device is larger.

t-Test: Two-Sample (Unequal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	At device	*At distance with highest mean*
Mean	34.40346	41.14558
Variance	109.5293	66.73441
Observations	138	195
df	248	
t Stat	-6.3259	
P(T<=t) two-tail	1.17E-09	
t Critical two-tail	1.969576	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.

E-7 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MEAN SPEEDS – MID-BLOCK NARROWING ON HAMILTON AVENUE, ILAM

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance at the device is smaller

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	P-value
0.9425	1.2902	0.6407

Since F <= Critical F, reject the null hypothesis.
The variance at the device is smaller.

t-Test: Two-Sample (Unequal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

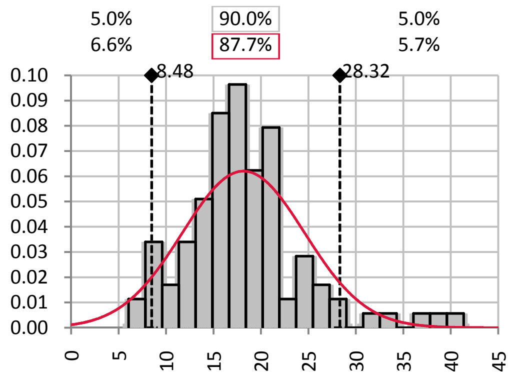
	At device	*At distance with highest mean*
Mean	43.505	44.89485
Variance	49.79227	52.83254
Observations	128	221
df	272	
t Stat	-1.75374	
P(T<=t) two-tail	0.080601	
t Critical two-tail	1.968724	

Since p > 0.05, accept the null hypothesis.
The means are the same.

Appendix F

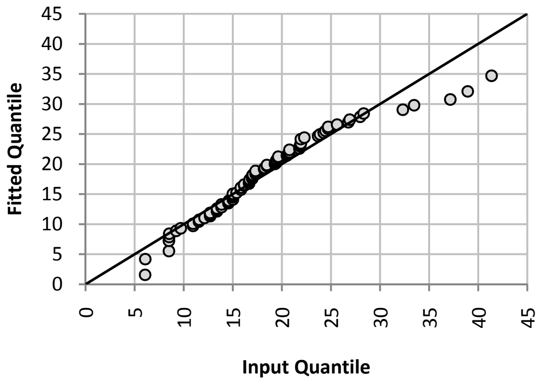
F-1 NORMALITY CHECKS FOR VEHICLE SPEEDS ON BURKE STREET, ADDINGTON (AT DEVICE)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Departures from normality are detected.

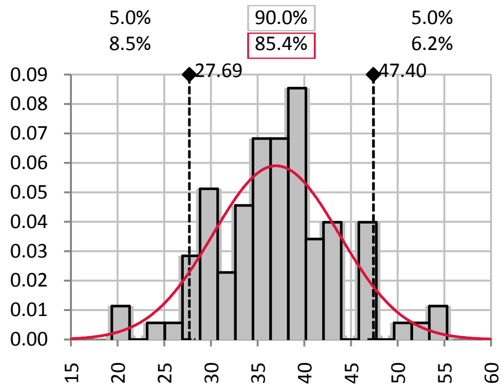
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.1092	0.0888	< 0.01	Reject H_o
Anderson-Darling	1.5960	0.7460	< 0.005	Reject H_o

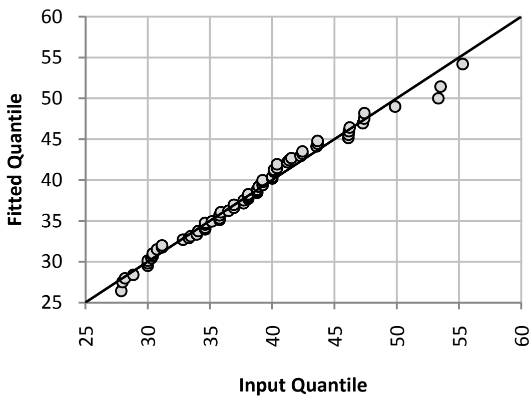
F-2 NORMALITY CHECKS FOR VEHICLE SPEEDS ON BURKE STREET, ADDINGTON (AT MID-POINT 1)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

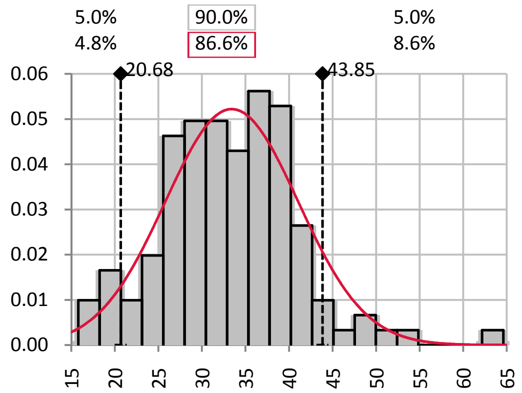
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0815	0.0921	0.10 – 0.15	Accept H_o
Anderson-Darling	0.4285	0.74580	> 0.25	Accept H_o

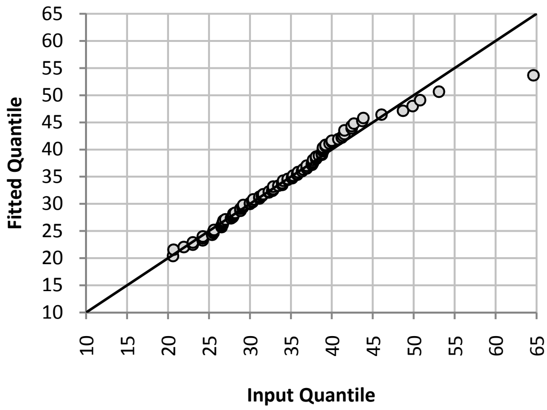
F-3 NORMALITY CHECKS FOR VEHICLE SPEEDS ON BURKE STREET, ADDINGTON (AT MID-POINT 2)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

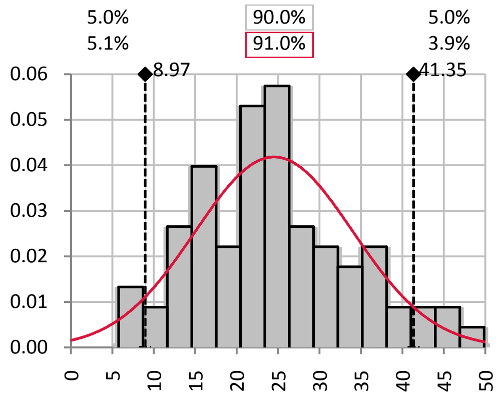
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0626	0.0799	> 0.15	Accept H_o
Anderson-Darling	0.4724	0.7474	0.15 – 0.25	Accept H_o

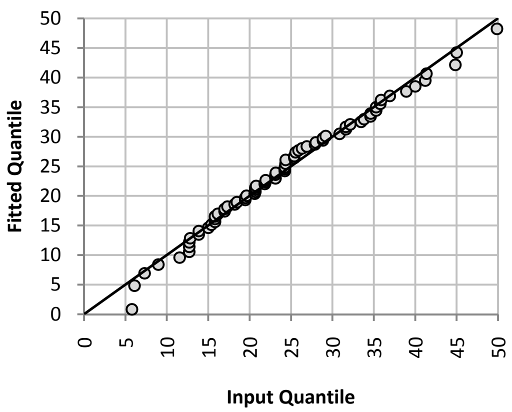
F-4 NORMALITY CHECKS FOR VEHICLE SPEEDS ON RANDOLPH STREET, WOOLSTON (AT DEVICE)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

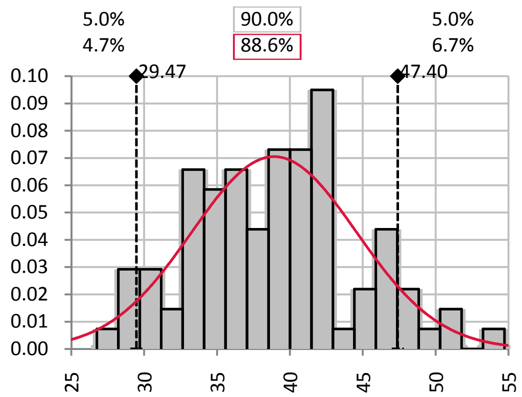
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0810	0.1010	> 0.15	Accept H_o
Anderson-Darling	0.3643	0.7445	> 0.25	Accept H_o

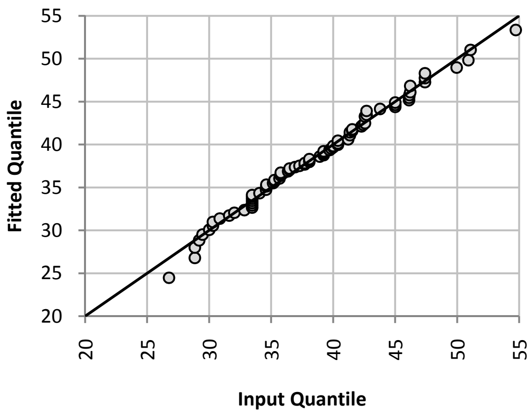
F-5 NORMALITY CHECKS FOR VEHICLE SPEEDS ON RANDOLPH STREET, WOOLSTON (AT MID-POINT 1)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

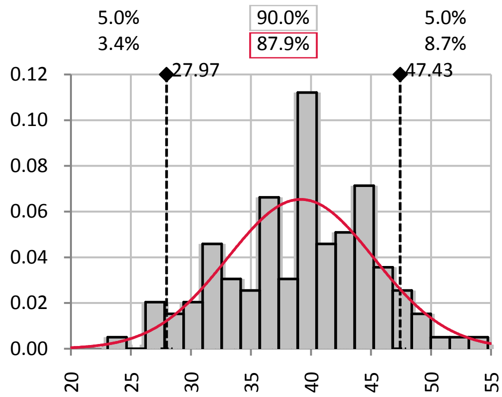
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0697	0.0921	> 0.15	Accept H_o
Anderson-Darling	0.3357	0.7458	> 0.25	Accept H_o

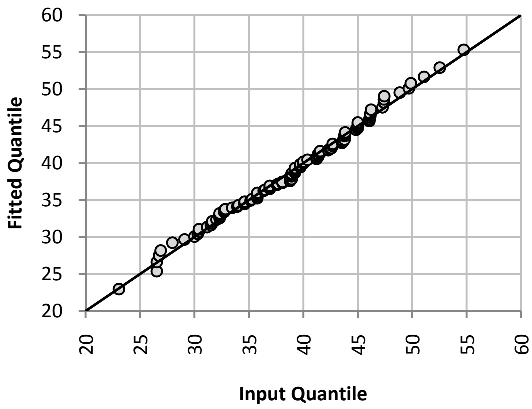
F-6 NORMALITY CHECKS FOR VEHICLE SPEEDS ON RANDOLPH STREET, WOOLSTON (AT MID-POINT 2)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

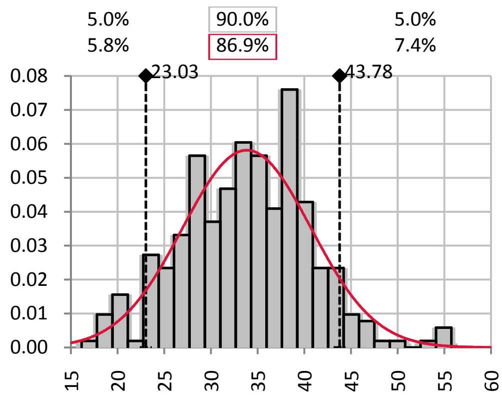
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0813	0.0799	< 0.01	Reject H_o
Anderson-Darling	0.4034	0.7474	0.025 – 0.05	Accept H_o

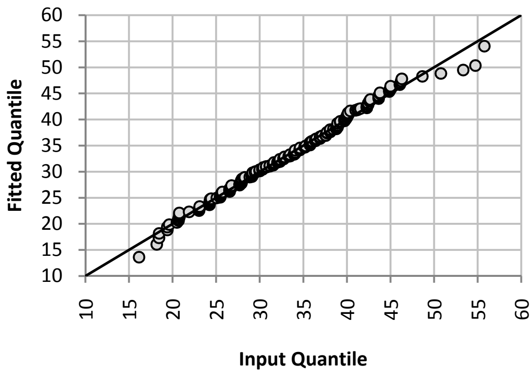
F-7 NORMALITY CHECKS FOR VEHICLE SPEEDS ON MACKENZIE AVENUE, WOOLSTON (AT DEVICE)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

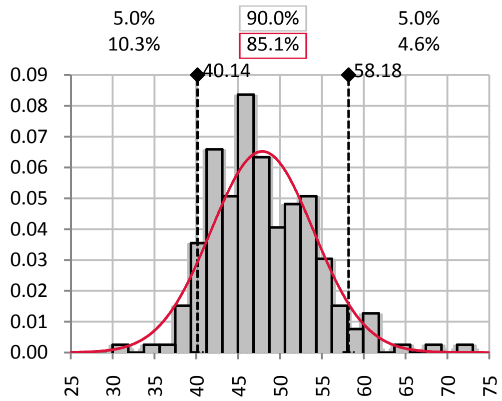
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0449	0.0506	0.10 – 0.15	Accept H_o
Anderson-Darling	0.6166	0.7502	0.10 – 0.15	Accept H_o

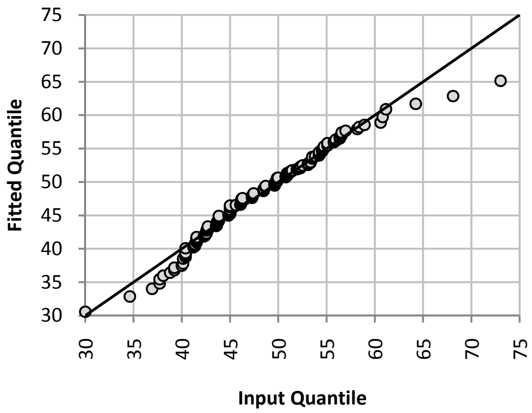
F-8 NORMALITY CHECKS FOR VEHICLE SPEEDS ON MACKENZIE AVENUE, WOOLSTON (AT MID-POINT 1)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Departures from normality are detected.

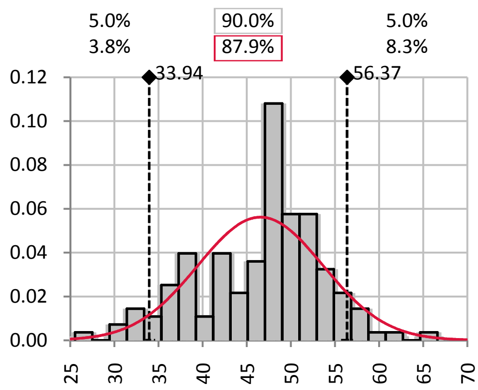
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0930	0.0614	< 0.01	Reject H_o
Anderson-Darling	0.1358	0.7493	< 0.005	Reject H_o

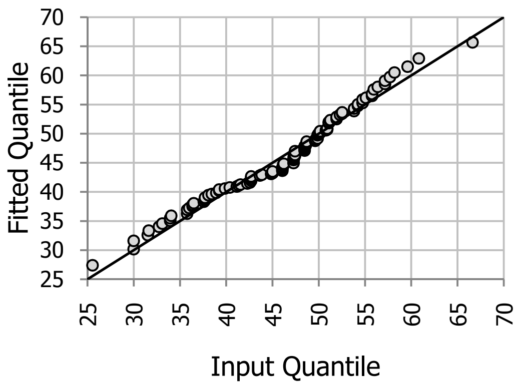
F-9 NORMALITY CHECKS FOR VEHICLE SPEEDS ON MACKENZIE AVENUE, WOOLSTON (AT MID-POINT 2)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

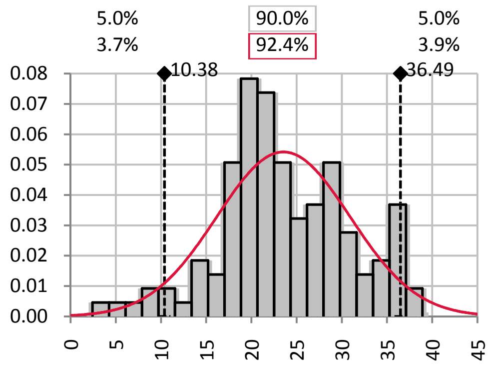
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.1344	0.0747	< 0.01	Reject H_o
Anderson-Darling	1.7253	0.7480	< 0.005	Reject H_o

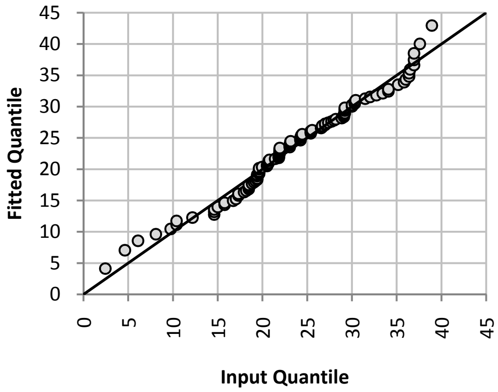
F-10 NORMALITY CHECKS FOR VEHICLE SPEEDS ON RATTRAY STREET, RICCARTON (AT DEVICE)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Departures from normality are detected.

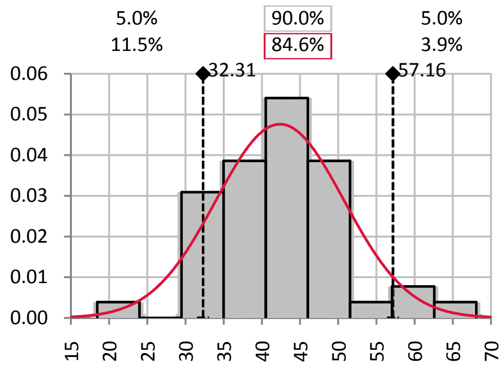
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0831	0.0815	0.025 – 0.05	Reject H_o
Anderson-Darling	0.8555	0.7472	0.025 – 0.05	Reject H_o

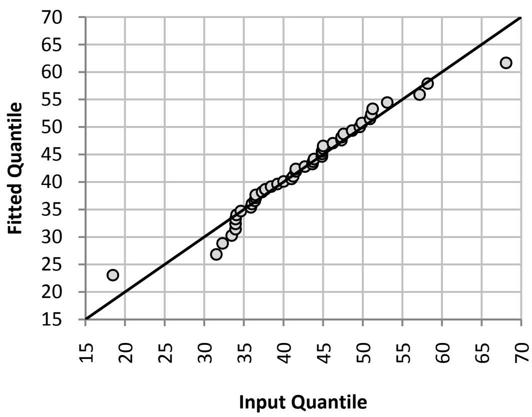
F-11 NORMALITY CHECKS FOR VEHICLE SPEEDS ON RATTRAY STREET, RICCARTON (AT MID-POINT 1)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

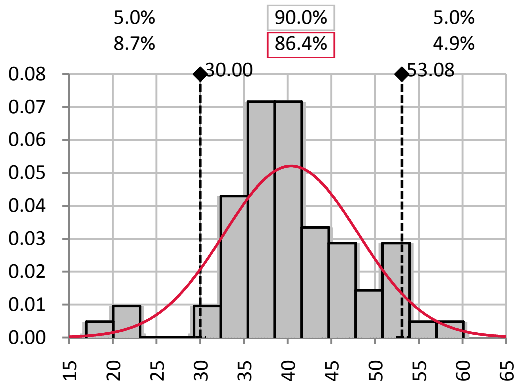
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0080	0.1284	> 0.15	Accept H_o
Anderson-Darling	0.4369	0.7394	> 0.25	Reject H_o

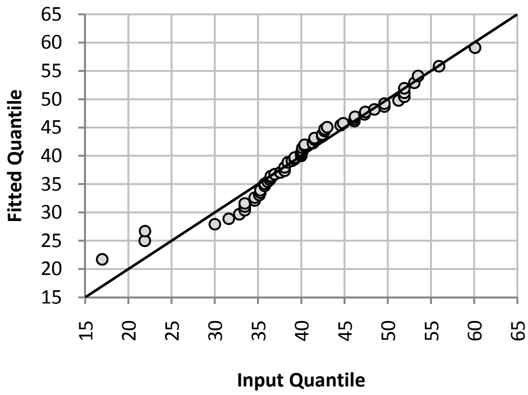
F-12 NORMALITY CHECKS FOR VEHICLE SPEEDS ON RATTRAY STREET, RICCARTON (AT MID-POINT 2)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Departures from normality are detected.

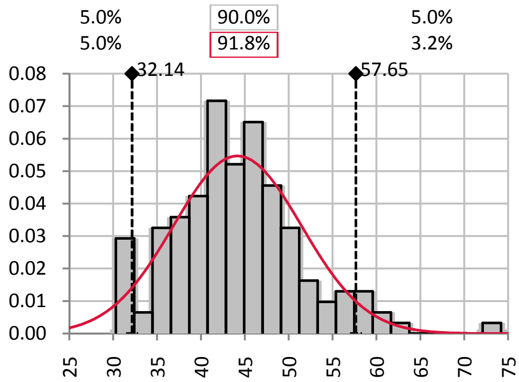
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.1034	0.1073	0.05 – 0.10	Accept H_o
Anderson-Darling	0.9173	0.7434	0.01 – 0.025	Reject H_o

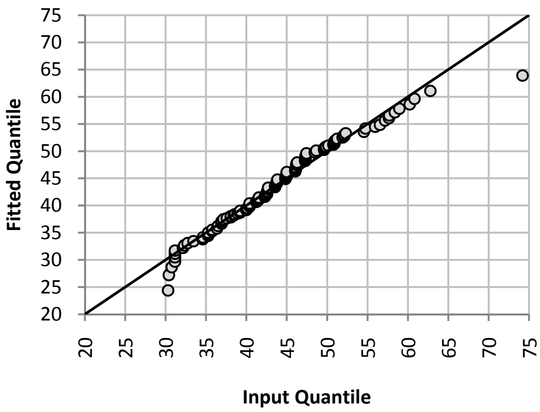
F-13 NORMALITY CHECKS FOR VEHICLE SPEEDS ON STRATFORD STREET, FENDALTON (AT DEVICE)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Departures from normality are detected.

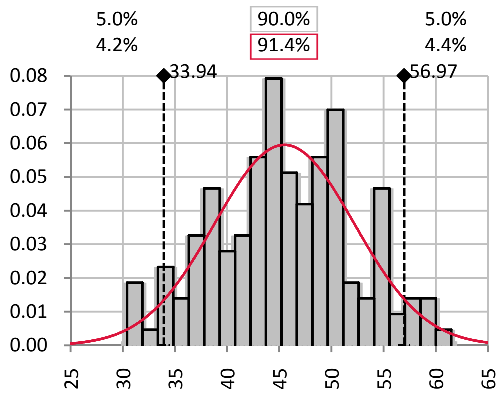
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.1024	0.0735	< 0.01	Reject H_o
Anderson-Darling	0.9823	0.7481	0.01 – 0.025	Reject H_o

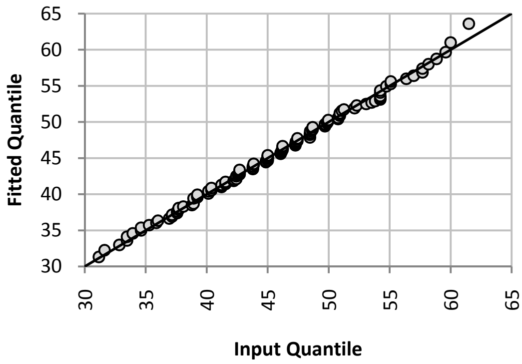
F-14 NORMALITY CHECKS FOR VEHICLE SPEEDS ON STRATFORD STREET, FENDALTON (AT MID-POINT 1)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

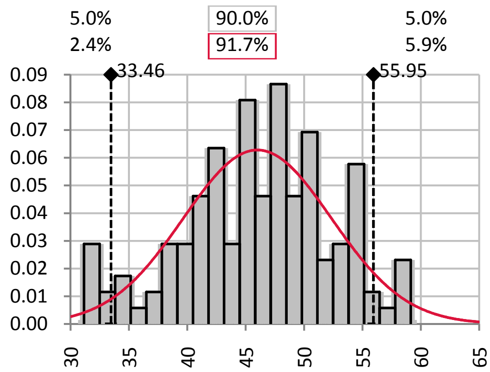
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0414	0.0740	> 0.15	Accept H_o
Anderson-Darling	0.2030	0.7481	> 0.25	Accept H_o

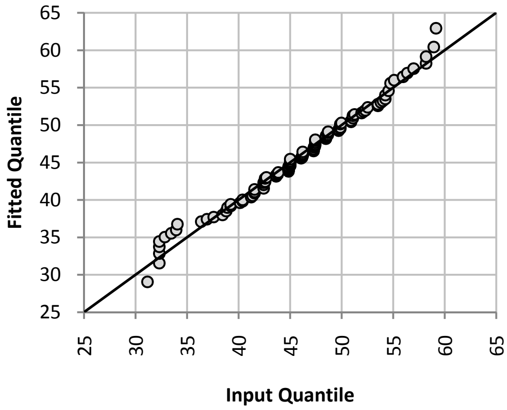
F-15 NORMALITY CHECKS FOR VEHICLE SPEEDS ON STRATFORD STREET, FENDALTON (AT MID-POINT 2)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

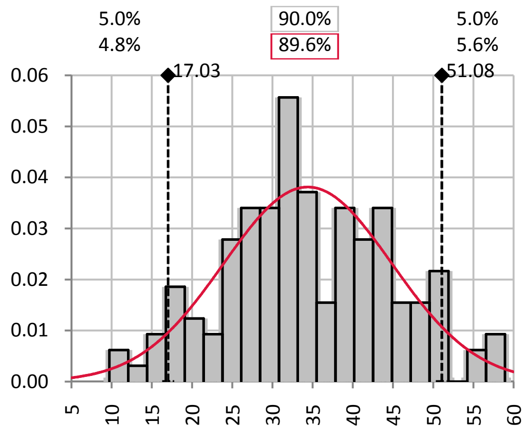
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0658	0.0781	> 0.15	Accept H_o
Anderson-Darling	0.4955	0.7476	0.15 – 0.25	Accept H_o

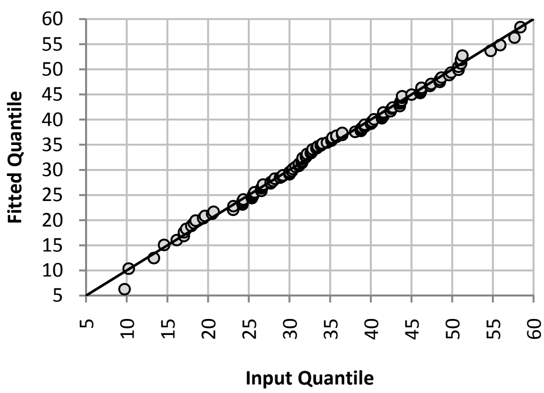
F-16 NORMALITY CHECKS FOR VEHICLE SPEEDS ON KIRKWOOD AVENUE, ILAM (AT DEVICE)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

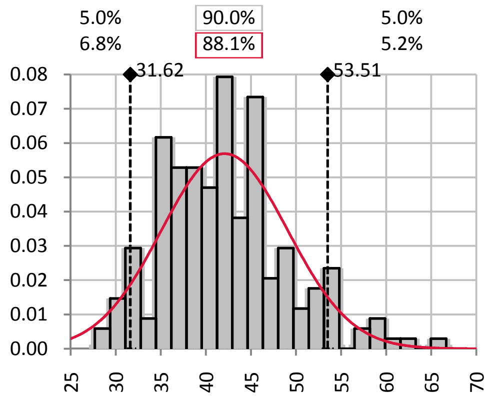
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0522	0.0758	> 0.15	Accept H_o
Anderson-Darling	0.3010	0.7478	> 0.25	Accept H_o

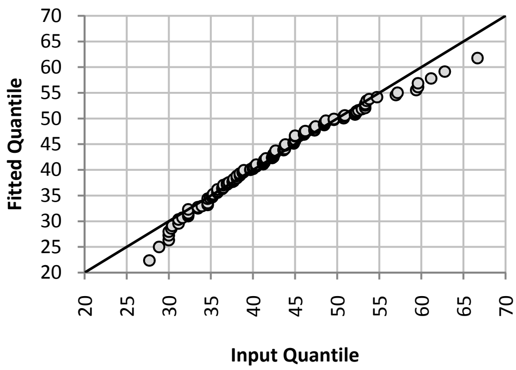
F-17 NORMALITY CHECKS FOR VEHICLE SPEEDS ON KIRKWOOD AVENUE, ILAM (AT MID-POINT 1)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Departures from normality are detected.

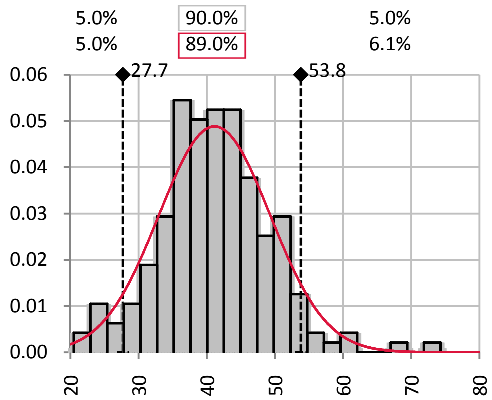
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0849	0.0629	< 0.01	Reject H_o
Anderson-Darling	1.1759	0.7492	< 0.005	Reject H_o

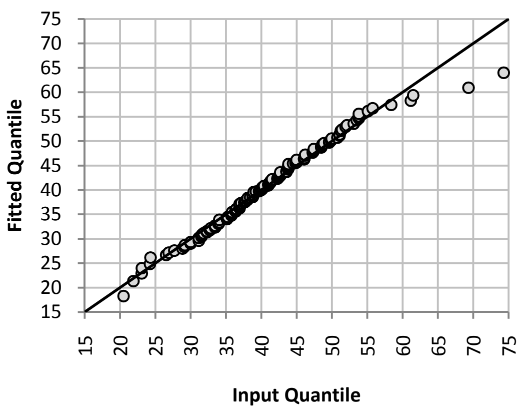
F-18 NORMALITY CHECKS FOR VEHICLE SPEEDS ON KIRKWOOD AVENUE, ILAM (AT MID-POINT 2)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Departures from normality are detected.

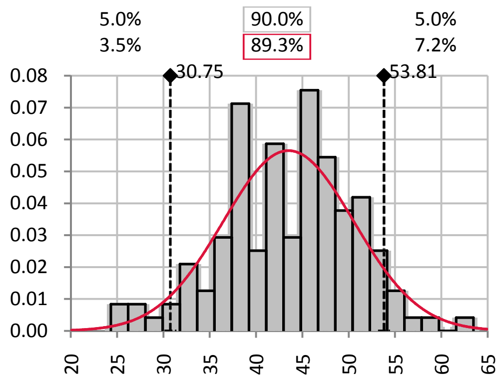
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0679	0.0639	0.025 – 0.05	Reject H_o
Anderson-Darling	0.6080	0.7491	0.10 – 0.15	Accept H_o

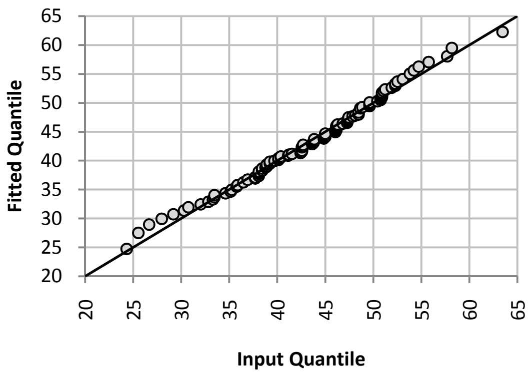
F-19 NORMALITY CHECKS FOR VEHICLE SPEEDS ON HAMILTON AVENUE, ILAM (AT DEVICE)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

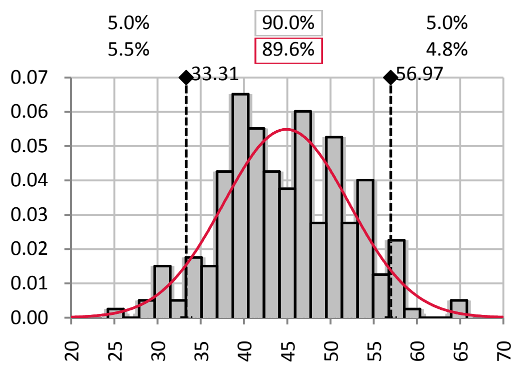
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0711	0.0787	0.10 – 0.15	Accept H_o
Anderson-Darling	0.4249	0.7475	> 0.25	Accept H_o

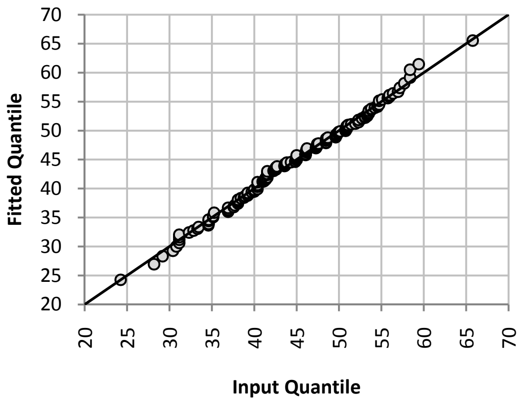
F-20 NORMALITY CHECKS FOR VEHICLE SPEEDS ON HAMILTON AVENUE, ILAM (AT MID-POINT 1)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

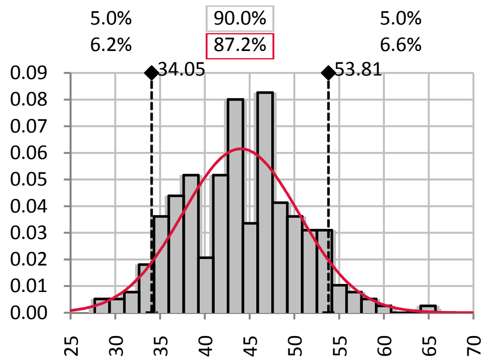
(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0761	0.0600	< 0.01	Reject H_o
Anderson-Darling	0.5805	0.7494	0.10 – 0.15	Accept H_o

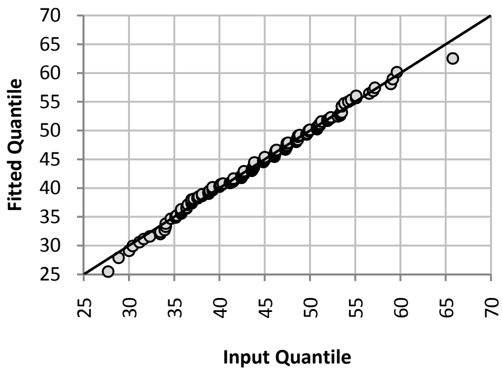
F-21 NORMALITY CHECKS FOR VEHICLE SPEEDS ON HAMILTON AVENUE, ILAM (AT MID-POINT 2)

(1) Frequency Histogram



The data seems to be normally distributed.

(2) Normal Q-Q Plot



Slight departures from normality are detected.

(3) Normality Tests

H_o: The data follows a normal distribution
H_a: The data does not follow a normal distribution

Test	Statistic	Critical Value (α = 0.05)	P-value	Conclusion
Kolmogorov-Smirnov	0.0478	0.0583	> 0.15	Accept H_o
Anderson-Darling	0.4602	0.7496	> 0.25	Accept H_o

Appendix G

G-1 F-TEST FOR EQUALITY OF VARIANCES IN SPEED – SPEED HUMP ON BURKE STREET, ADDINGTON

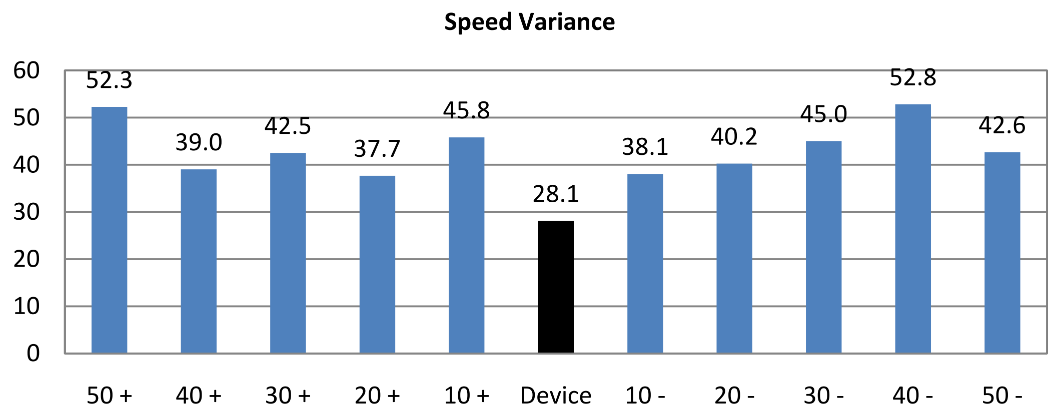
Test hypotheses:

H_o : The variances are equal

H_a : The variance at the device is smaller

Distance to device (m)	F	Critical F	p-value	Conclusion	Inference
10	0.6133	1.4028	0.9847	Reject H_o	The variance at the device is smaller
20	0.7459	1.4494	0.8915	Reject H_o	The variance at the device is smaller
30	0.6608	1.4623	0.9570	Reject H_o	The variance at the device is smaller
40	0.7200	1.4689	0.9121	Reject H_o	The variance at the device is smaller
50	0.5376	1.5050	0.9928	Reject H_o	The variance at the device is smaller

Distance from device (m)	F	Critical F	p-value	Conclusion	Inference
10	0.7381	1.4011	0.9123	Reject H_o	The variance at the device is smaller
20	0.6980	1.4294	0.9392	Reject H_o	The variance at the device is smaller
30	0.6238	1.4742	0.9731	Reject H_o	The variance at the device is smaller
40	0.5319	1.4689	0.9950	Reject H_o	The variance at the device is smaller
50	0.6588	1.4780	0.9555	Reject H_o	The variance at the device is smaller



G-2 F-TEST FOR EQUALITY OF VARIANCES IN SPEED – SPEED TABLE ON RANDOLPH STREET, WOOLSTON

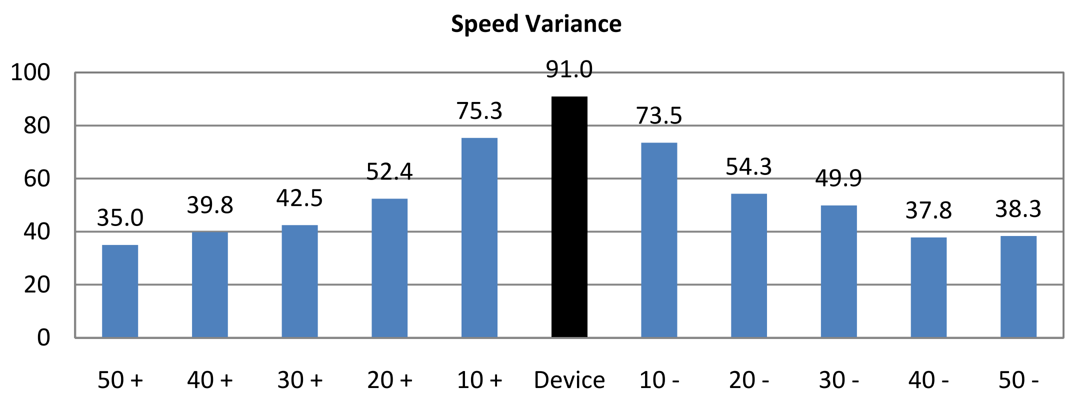
Test hypotheses:

H_o : The variances are equal

H_a : The variance at the device is larger

Distance to device (m)	F	Critical F	p-value	Conclusion	Inference
10	1.2078	1.3689	0.1606	Accept Ho	The variances are equal
20	1.7360	1.3880	0.0028	Reject Ho	The variance at the device is larger
30	2.1425	1.3880	0.0001	Reject Ho	The variance at the device is larger
40	2.2878	1.4011	0.0000	Reject Ho	The variance at the device is larger
50	2.5994	1.4106	0.0000	Reject Ho	The variance at the device is larger

Distance from device (m)	F	Critical F	p-value	Conclusion	Inference
10	1.2375	1.3745	0.1348	Accept Ho	The variances are equal
20	1.6760	1.3757	0.0038	Reject Ho	The variance at the device is larger
30	1.8236	1.4001	0.0017	Reject Ho	The variance at the device is larger
40	2.4073	1.3865	0.0000	Reject Ho	The variance at the device is larger
50	2.3742	1.3992	0.0000	Reject Ho	The variance at the device is larger



G-3 F-TEST FOR EQUALITY OF VARIANCES IN SPEED – ANGLED SLOW POINT ON MACKENZIE AVENUE, WOOLSTON

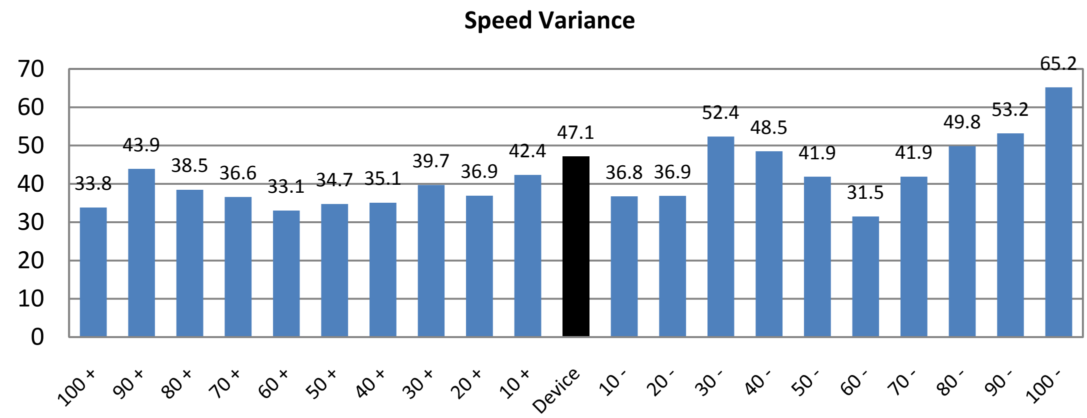
Test hypotheses:

H_o : The variances are equal

H_a : The variance at the device is larger

Distance to device (m)	F	Critical F	p-value	Conclusion	Inference
10	1.1129	1.3014	0.2538	Accept Ho	The variances are equal
20	1.2760	1.3039	0.0653	Accept Ho	The variances are equal
30	1.1873	1.3253	0.1582	Accept Ho	The variances are equal
40	1.3433	1.3253	0.0424	Reject Ho	The variance at the device is larger
50	1.3568	1.3338	0.0408	Reject Ho	The variance at the device is larger
60	1.4260	1.3338	0.0217	Reject Ho	The variance at the device is larger
70	1.2884	1.3338	0.0738	Accept Ho	The variances are equal
80	1.2250	1.3514	0.1338	Accept Ho	The variances are equal
90	1.0727	1.3652	0.3622	Accept Ho	The variances are equal
100	1.3938	1.3676	0.0406	Reject Ho	The variance at the device is larger

Distance from device (m)	F	Critical F	p-value	Conclusion	Inference
10	1.2820	1.3161	0.0683	Accept Ho	The variances are equal
20	1.2781	1.3190	0.0723	Accept Ho	The variances are equal
30	0.9003	1.3452	0.7420	Accept Ho	The variances are equal
40	0.9715	1.3269	0.5811	Accept Ho	The variances are equal
50	1.1256	1.3356	0.2528	Accept Ho	The variances are equal
60	1.4966	1.3412	0.0124	Reject Ho	The variance at the device is larger
70	1.1251	1.3514	0.2625	Accept Ho	The variances are equal
80	0.9458	1.3514	0.6386	Accept Ho	The variances are equal
90	0.8861	1.3652	0.7635	Accept Ho	The variances are equal
100	0.7230	1.3676	0.9708	Accept Ho	The variances are equal



G-4 F-TEST FOR EQUALITY OF VARIANCES IN SPEED – ANGLED SLOW POINT ON RATTRAY STREET, RICCARTON

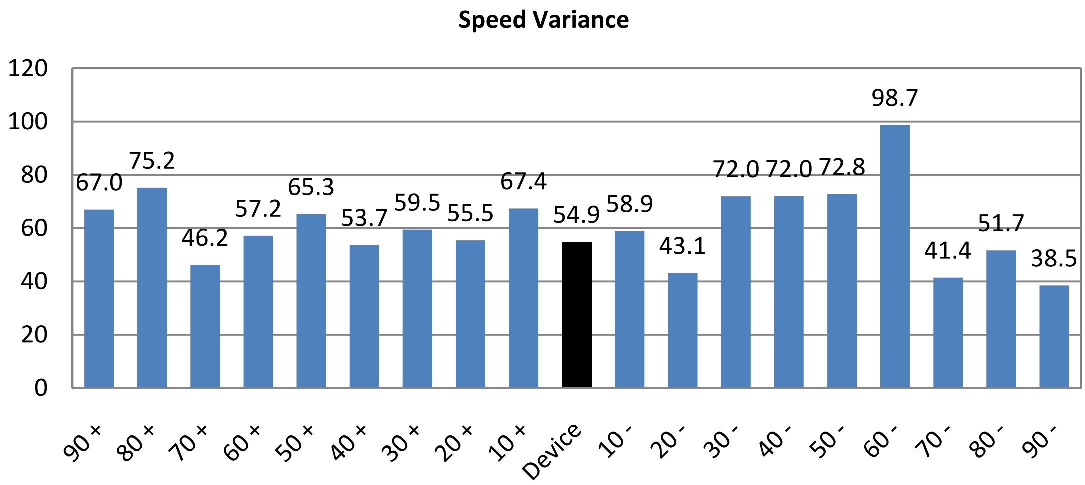
Test hypotheses:

H_o : The variances are equal

H_a : The variance at the device is smaller

Distance to device (m)	F-test				
	F	Critical F	p-value	Conclusion	Inference
10	0.8267	1.4224	0.8413	Reject Ho	The variance at the device is smaller
20	1.0048	1.4224	0.5064	Reject Ho	The variance at the device is smaller
30	0.9370	1.4467	0.6388	Reject Ho	The variance at the device is smaller
40	1.0386	1.5000	0.4548	Reject Ho	The variance at the device is smaller
50	0.8533	1.6022	0.7541	Reject Ho	The variance at the device is smaller
60	0.9749	1.6022	0.5649	Reject Ho	The variance at the device is smaller
70	1.2052	1.7018	0.2892	Reject Ho	The variance at the device is smaller
80	0.7411	1.8392	0.8548	Reject Ho	The variance at the device is smaller
90	0.8318	1.9859	0.7369	Reject Ho	The variance at the device is smaller

Distance from device (m)	F-test				
	F	Critical F	p-value	Conclusion	Inference
10	0.9464	1.3991	0.6261	Reject Ho	The variance at the device is smaller
20	1.2918	1.4607	0.1330	Reject Ho	The variance at the device is smaller
30	0.7744	1.5279	0.8782	Reject Ho	The variance at the device is smaller
40	0.7738	1.5807	0.8657	Reject Ho	The variance at the device is smaller
50	0.7656	1.8110	0.8326	Reject Ho	The variance at the device is smaller
60	0.5644	1.8392	0.9777	Reject Ho	The variance at the device is smaller
70	1.3454	2.0346	0.2520	Reject Ho	The variance at the device is smaller
80	1.0785	1.9859	0.4575	Reject Ho	The variance at the device is smaller
90	1.4477	2.1545	0.2174	Reject Ho	The variance at the device is smaller



G-5 F-TEST FOR EQUALITY OF VARIANCES IN SPEED – MID-BLOCK NARROWING ON STRATFORD STREET, FENDALTON

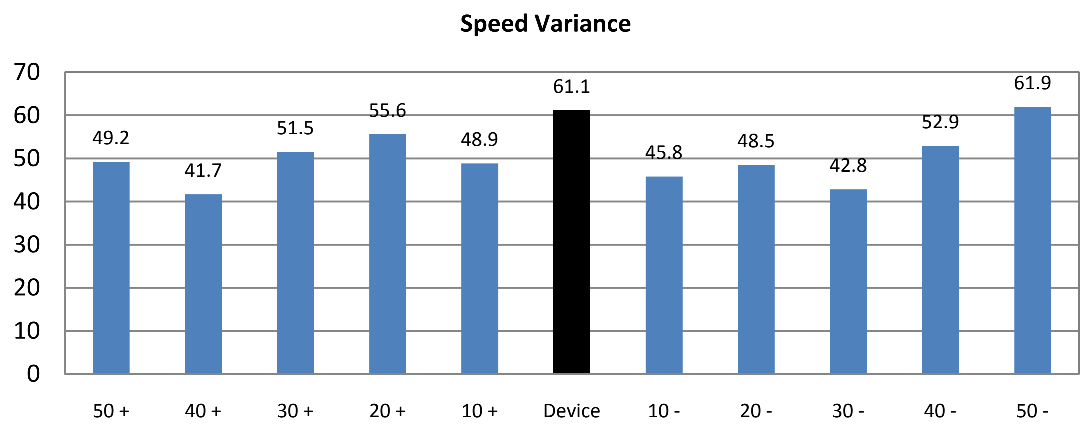
Test hypotheses:

H_o : The variances are equal

H_a : The variance at the device is larger

Distance to device (m)	F	Critical F	p-value	Conclusion	Inference
10	1.0907	1.4275	0.3485	Accept Ho	The variances are equal
20	0.9580	1.3989	0.5936	Accept Ho	The variances are equal
30	1.0342	1.4435	0.4488	Accept Ho	The variances are equal
40	1.2783	1.4135	0.1214	Accept Ho	The variances are equal
50	1.0834	1.4217	0.3584	Accept Ho	The variances are equal

Distance from device (m)	F	Critical F	p-value	Conclusion	Inference
10	1.1633	1.4245	0.2423	Accept Ho	The variances are equal
20	1.0984	1.4189	0.3331	Accept Ho	The variances are equal
30	1.2442	1.4189	0.1521	Accept Ho	The variances are equal
40	1.0067	1.4401	0.4986	Accept Ho	The variances are equal
50	0.8604	1.3843	0.7886	Accept Ho	The variances are equal



G-6 F-TEST FOR EQUALITY OF VARIANCES IN SPEED – MID-BLOCK NARROWING ON KIRKWOOD AVENUE, ILAM

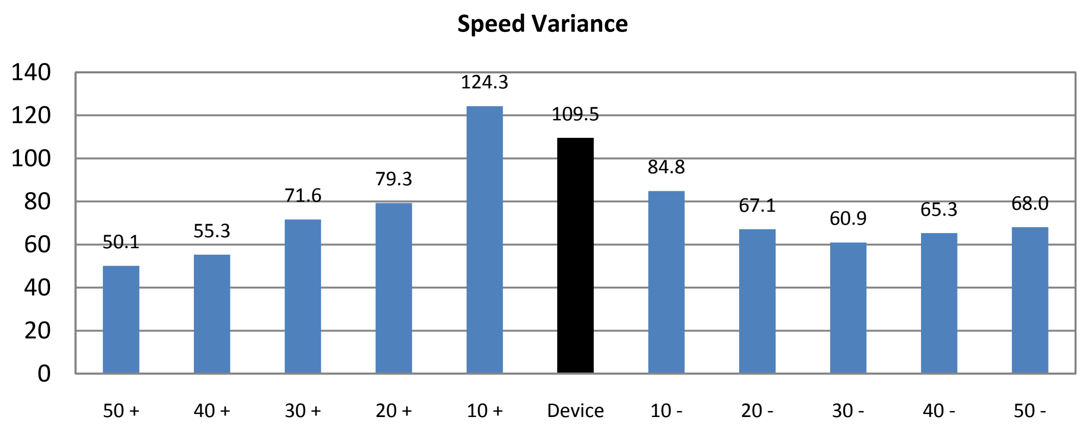
Test hypotheses:

H_o : The variances are equal

H_a : The variance at the device is larger

Distance to device (m)	F	Critical F	p-value	Conclusion	Inference
10	0.8814	1.3465	0.7613	Accept Ho	The variances are equal
20	1.3816	1.3335	0.0324	Reject Ho	The variance at the device is larger
30	1.5291	1.3511	0.0103	Reject Ho	The variance at the device is larger
40	1.9809	1.3655	0.0002	Reject Ho	The variance at the device is larger
50	2.1861	1.3499	0.0000	Reject Ho	The variance at the device is larger

Distance from device (m)	F	Critical F	p-value	Conclusion	Inference
10	1.2912	1.3443	0.0776	Accept Ho	The variances are equal
20	1.6321	1.3599	0.0046	Reject Ho	The variance at the device is larger
30	1.7973	1.3573	0.0009	Reject Ho	The variance at the device is larger
40	1.6771	1.3655	0.0033	Reject Ho	The variance at the device is larger
50	1.6097	1.3763	0.0073	Reject Ho	The variance at the device is larger



G-7 F-TEST FOR EQUALITY OF VARIANCES IN SPEED – MID-BLOCK NARROWING ON HAMILTON AVENUE, ILAM

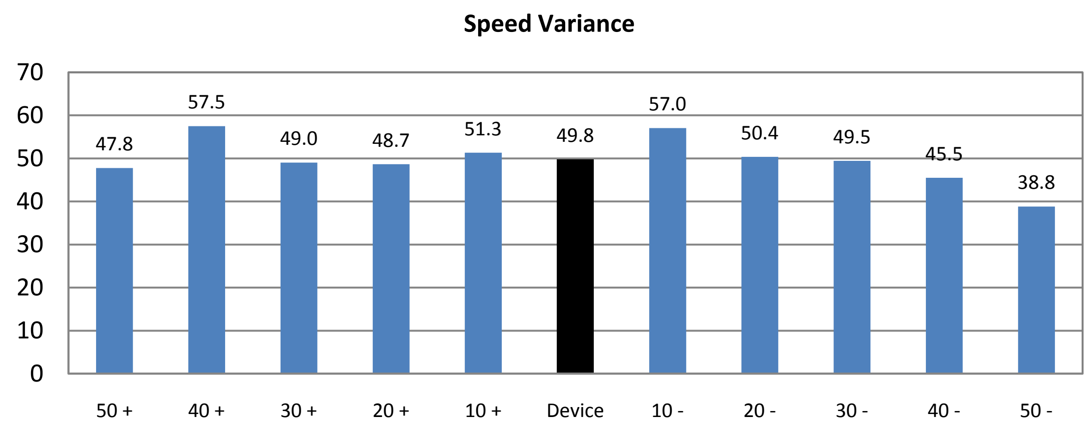
Test hypotheses:

H_o : The variances are equal

H_a : The variance at the device is larger

Distance to device (m)	F	Critical F	p-value	Conclusion	Inference
10	0.9699	1.3452	0.5679	Accept Ho	The variances are equal
20	1.0234	1.3452	0.4492	Accept Ho	The variances are equal
30	1.0155	1.3472	0.4667	Accept Ho	The variances are equal
40	0.8658	1.3558	0.7850	Accept Ho	The variances are equal
50	1.0422	1.3618	0.4141	Accept Ho	The variances are equal

Distance from device (m)	F	Critical F	p-value	Conclusion	Inference
10	0.8731	1.3414	0.7769	Accept Ho	The variances are equal
20	0.9884	1.3492	0.5264	Accept Ho	The variances are equal
30	1.0069	1.3524	0.4862	Accept Ho	The variances are equal
40	1.0939	1.3547	0.3136	Accept Ho	The variances are equal
50	1.2829	1.3482	0.0850	Accept Ho	The variances are equal



Appendix H

H-1 OUTPUTS FOR REGRESSION ANALYSIS USING S-CURVE FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED HUMPS)

Model Summary (85th Percentile Speed)

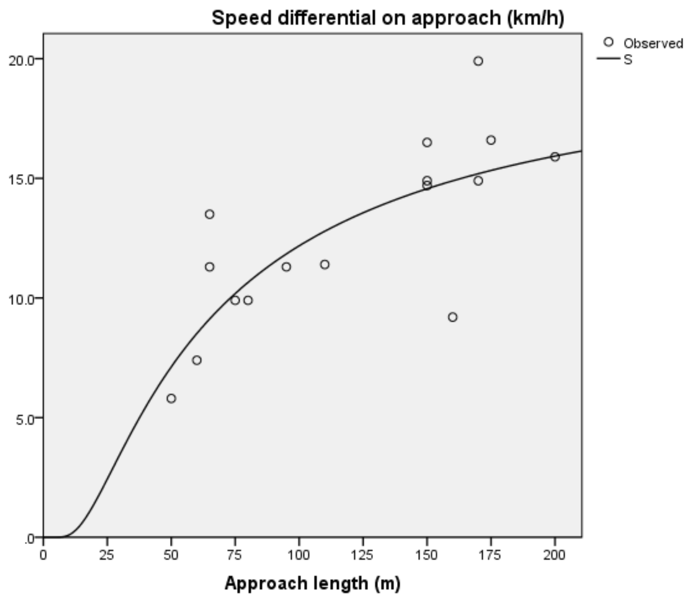
R	R Square	Adjusted R Square	Std. Error of the Estimate
.787	.620	.593	.209

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.995	1	.995	22.814	.000
Residual	.611	14	.044		
Total	1.606	15			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Approach length (m)	-53.676	11.238	-.787	-4.776	.000
(Constant)	3.037	.125		24.303	.000



Model Summary (Mean Speed)

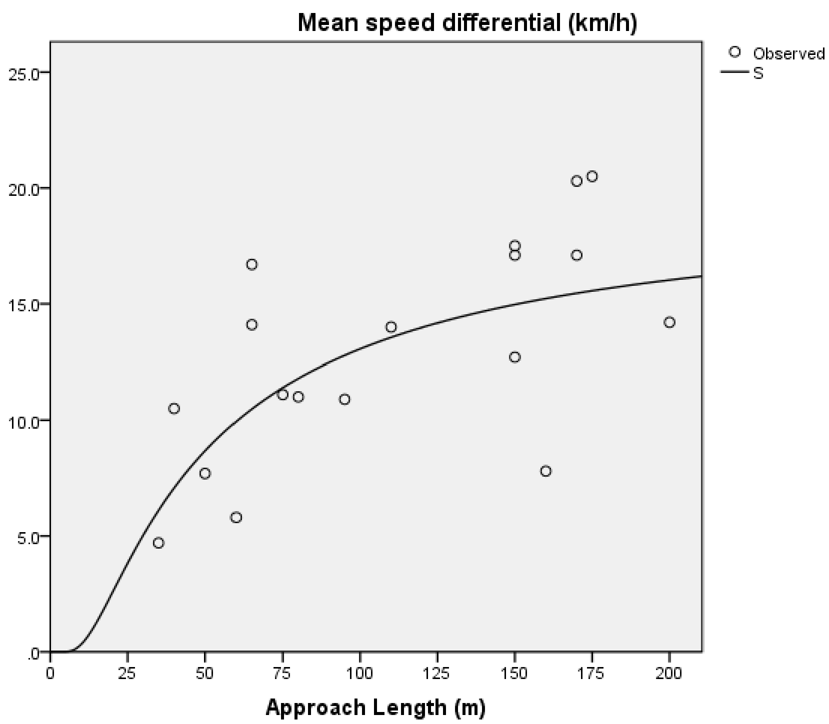
R	R Square	Adjusted R Square	Std. Error of the Estimate
.690	.476	.444	.312

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1.418	1	1.418	14.556	.002
Residual	1.559	16	.097		
Total	2.977	17			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Approach Length (m)	-40.926	10.727	-.690	-3.815	.002
(Constant)	2.979	.148		20.149	.000



H-2 OUTPUTS FOR REGRESSION ANALYSIS USING POWER FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED HUMPS)

Model Summary (85th Percentile Speed)

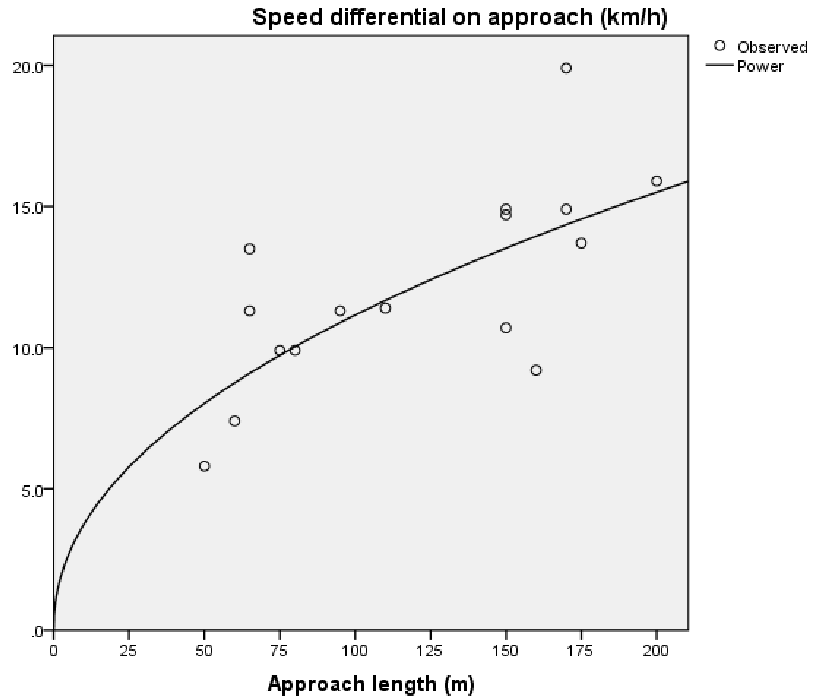
R	R Square	Adjusted R Square	Std. Error of the Estimate
.713	.509	.474	.223

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.721	1	.721	14.491	.002
Residual	.696	14	.050		
Total	1.417	15			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach length (m))	.475	.125	.713	3.807	.002
(Constant)	1.251	.736		1.698	.112



Model Summary (Mean Speed)

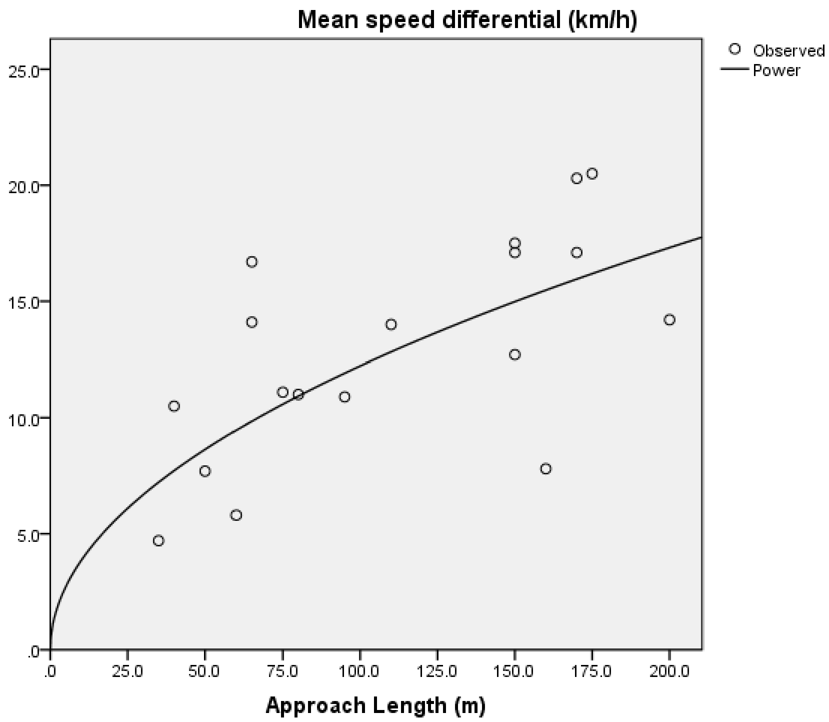
R	R Square	Adjusted R Square	Std. Error of the Estimate
.667	.445	.410	.321

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1.324	1	1.324	12.812	.003
Residual	1.653	16	.103		
Total	2.977	17			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach Length (m))	.502	.140	.667	3.579	.003
(Constant)	1.212	.783		1.547	.141



H-3 OUTPUTS FOR REGRESSION ANALYSIS USING LOGARITHMIC FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED HUMPS)

Model Summary (85th Percentile Speed)

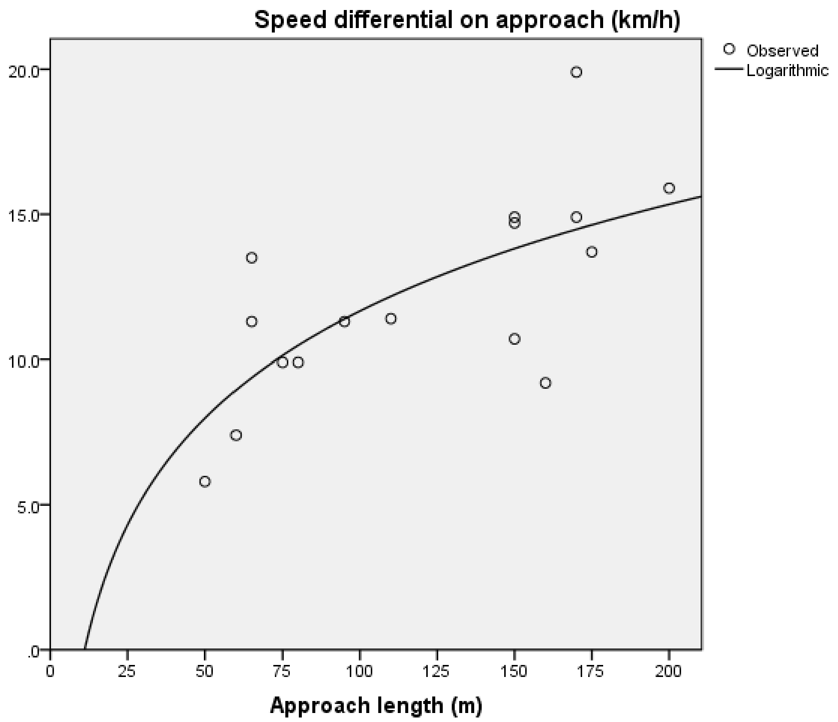
R	R Square	Adjusted R Square	Std. Error of the Estimate
.696	.484	.447	2.617

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	89.946	1	89.946	13.137	.003
Residual	95.854	14	6.847		
Total	185.800	15			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach length (m))	5.308	1.464	.696	3.625	.003
(Constant)	-12.779	6.909		-1.850	.086



Model Summary (Mean Speed)

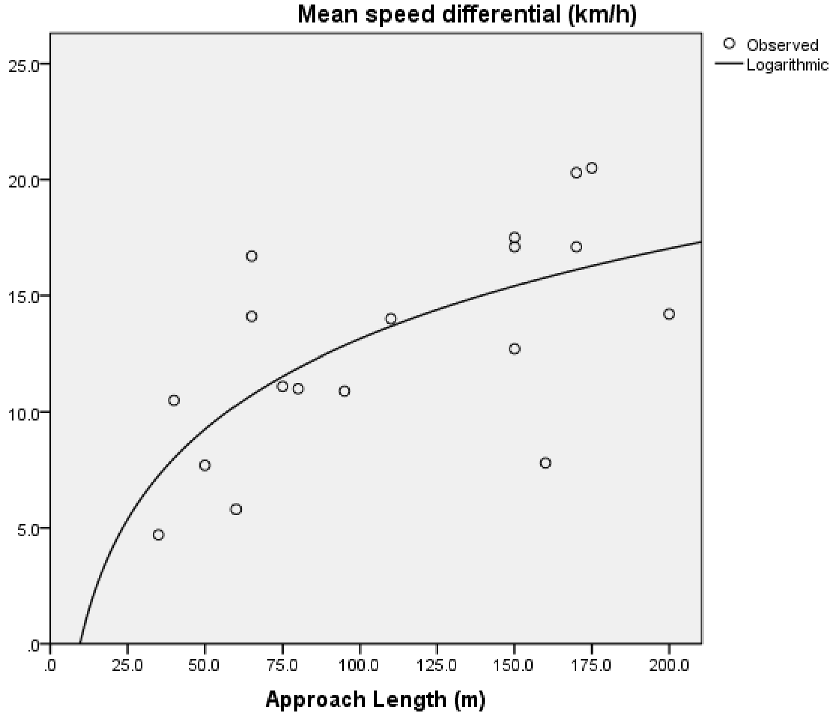
R	R Square	Adjusted R Square	Std. Error of the Estimate
.664	.441	.406	3.620

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	165.306	1	165.306	12.615	.003
Residual	209.659	16	13.104		
Total	374.965	17			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach Length (m))	5.608	1.579	.664	3.552	.003
(Constant)	-12.689	7.278		-1.743	.100



H-4 OUTPUTS FOR REGRESSION ANALYSIS USING LINEAR FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED HUMPS)

Model Summary (85th Percentile Speed)

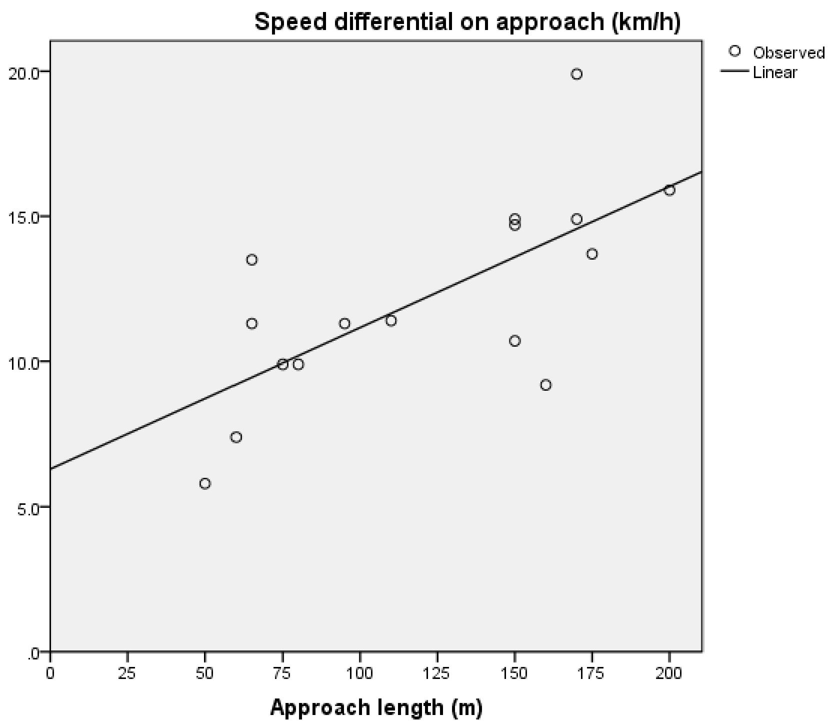
R	R Square	Adjusted R Square	Std. Error of the Estimate
.692	.479	.442	2.630

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	88.987	1	88.987	12.868	.003
Residual	96.813	14	6.915		
Total	185.800	15			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Approach length (m)	.049	.014	.692	3.587	.003
(Constant)	6.299	1.759		3.582	.003



Model Summary (Mean Speed)

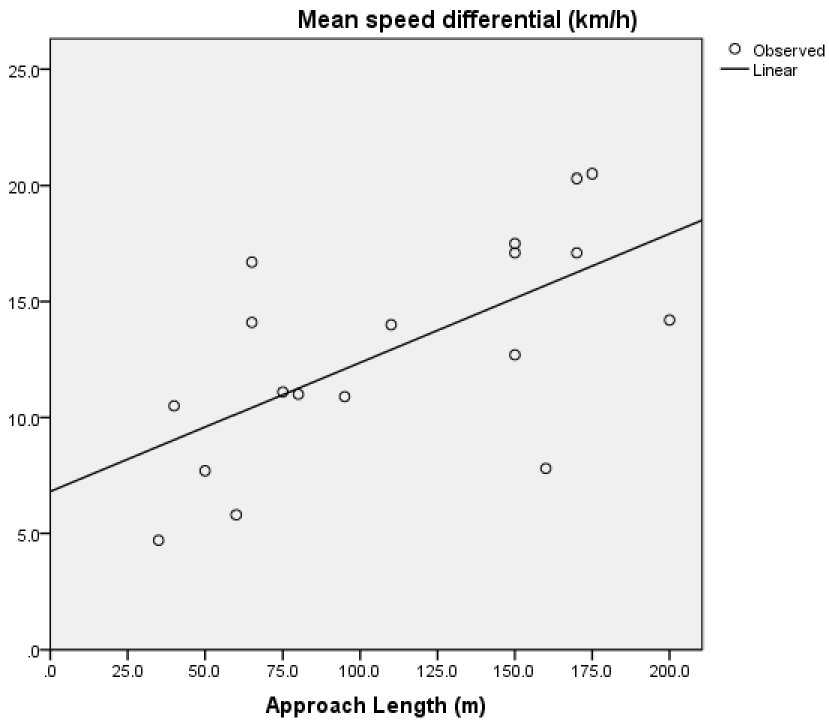
R	R Square	Adjusted R Square	Std. Error of the Estimate
.641	.410	.374	3.717

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	153.914	1	153.914	11.141	.004
Residual	221.051	16	13.816		
Total	374.965	17			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
Approach Length (m)	.056	.017	.641	3.338	.004
(Constant)	6.808	2.047		3.326	.004



H-5 OUTPUTS FOR REGRESSION ANALYSIS USING S-CURVE FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED TABLES)

Model Summary (85th Percentile Speed)

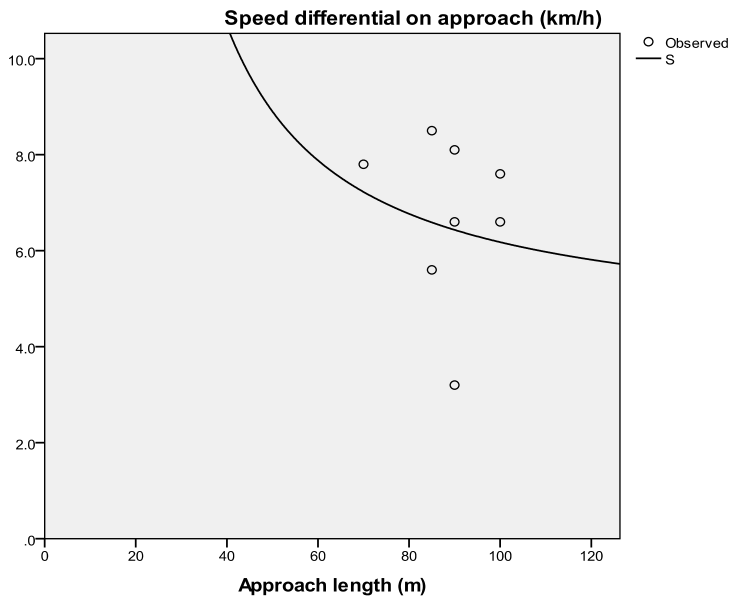
R	R Square	Adjusted R Square	Std. Error of the Estimate
.156	.024	-.138	.338

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.017	1	.017	.149	.713
Residual	.686	6	.114		
Total	.703	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Approach length (m)	36.518	94.641	.156	.386	.713
(Constant)	1.456	1.085		1.342	.228



Model Summary (Mean Speed)

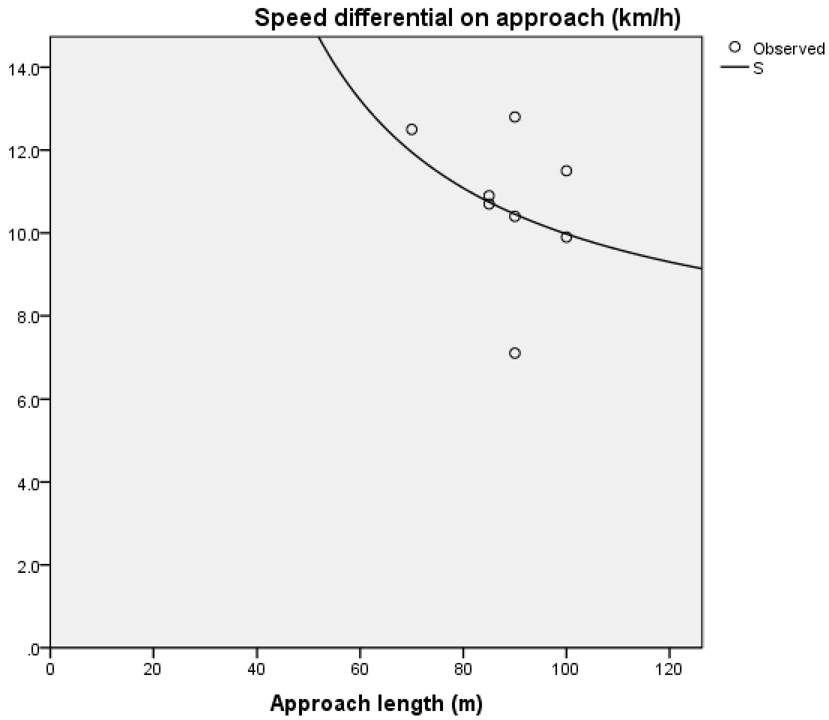
R	R Square	Adjusted R Square	Std. Error of the Estimate
.310	.096	-.055	.189

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.023	1	.023	.637	.455
Residual	.213	6	.036		
Total	.236	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Approach length (m)	42.123	52.766	.310	.798	.455
(Constant)	1.879	.605		3.106	.021



H-6 OUTPUTS FOR REGRESSION ANALYSIS USING POWER FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED TABLES)

Model Summary (85th Percentile Speed)

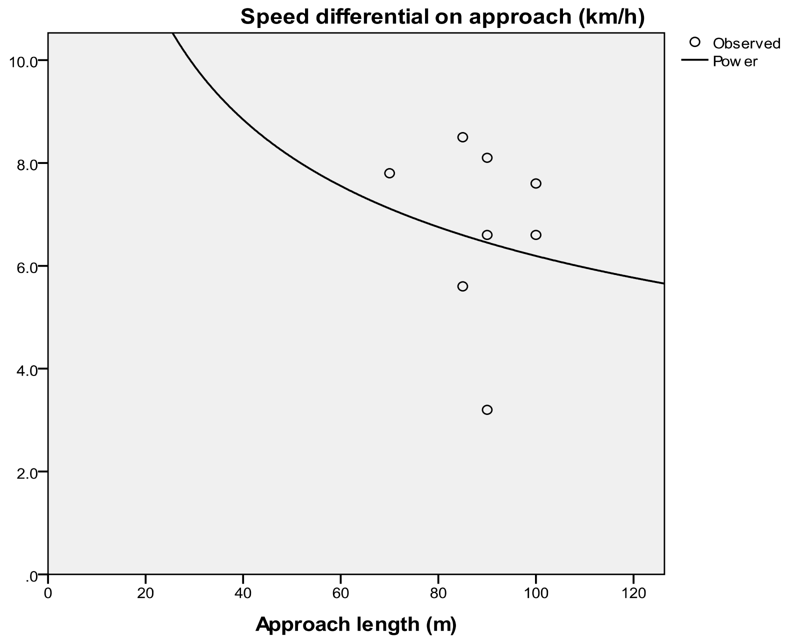
R	R Square	Adjusted R Square	Std. Error of the Estimate
.138	.019	-.144	.339

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.013	1	.013	.117	.744
Residual	.690	6	.115		
Total	.703	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach length (m))	-.389	1.137	-.138	-.342	.744
(Constant)	37.095	189.024		.196	.851



Model Summary (Mean Speed)

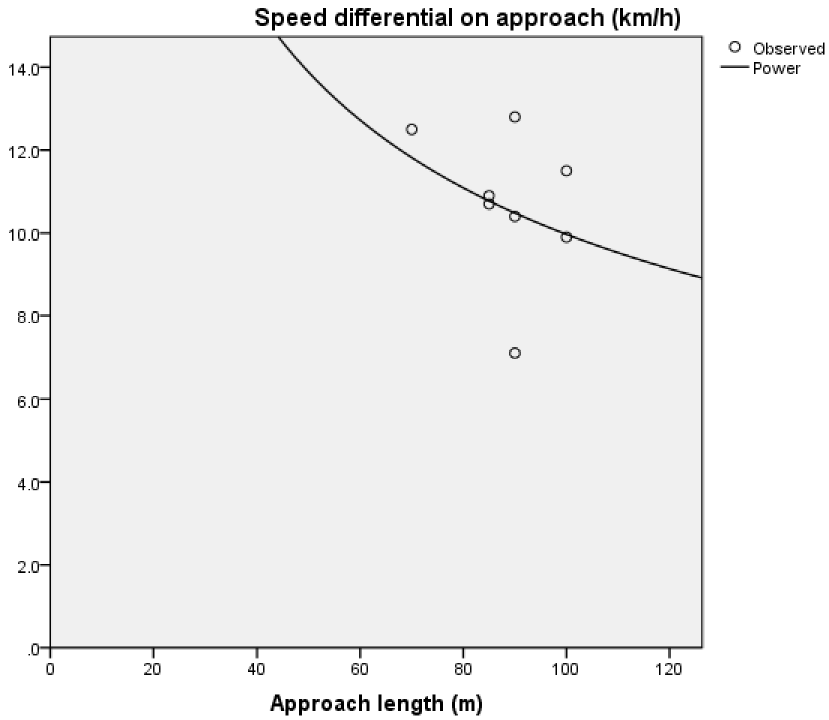
R	R Square	Adjusted R Square	Std. Error of the Estimate
.293	.086	-.066	.190

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.020	1	.020	.565	.481
Residual	.216	6	.036		
Total	.236	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach length (m))	-.478	.636	-.293	-.752	.481
(Constant)	90.040	256.535		.351	.738



H-7 OUTPUTS FOR REGRESSION ANALYSIS USING LOGARITHMIC FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED TABLES)

Model Summary (85th Percentile Speed)

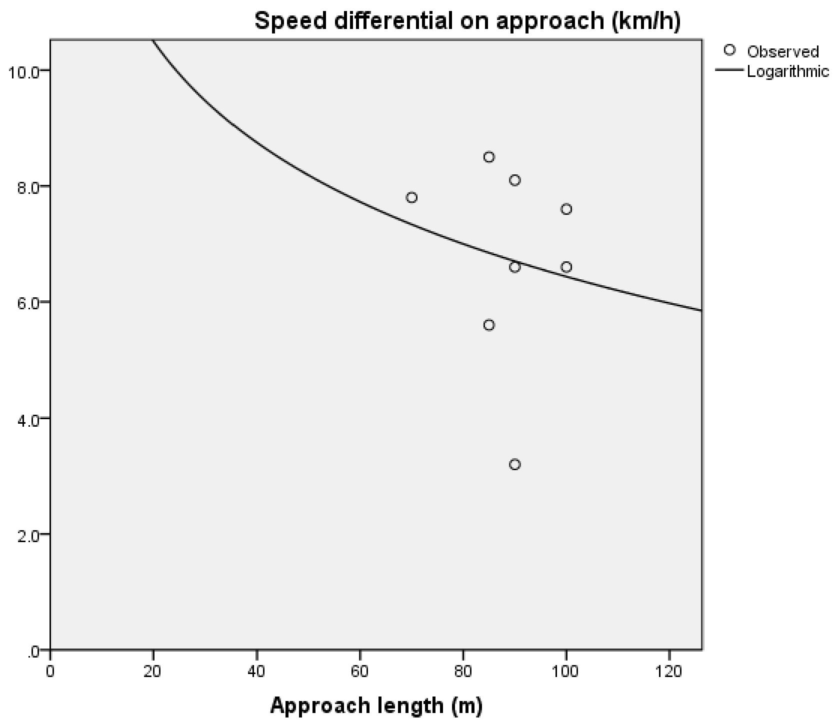
R	R Square	Adjusted R Square	Std. Error of the Estimate
.166	.027	-.135	1.831

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.567	1	.567	.169	.695
Residual	20.113	6	3.352		
Total	20.680	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach length (m))	-2.525	6.141	-.166	-.411	.695
(Constant)	18.061	27.521		.656	.536



Model Summary (Mean Speed)

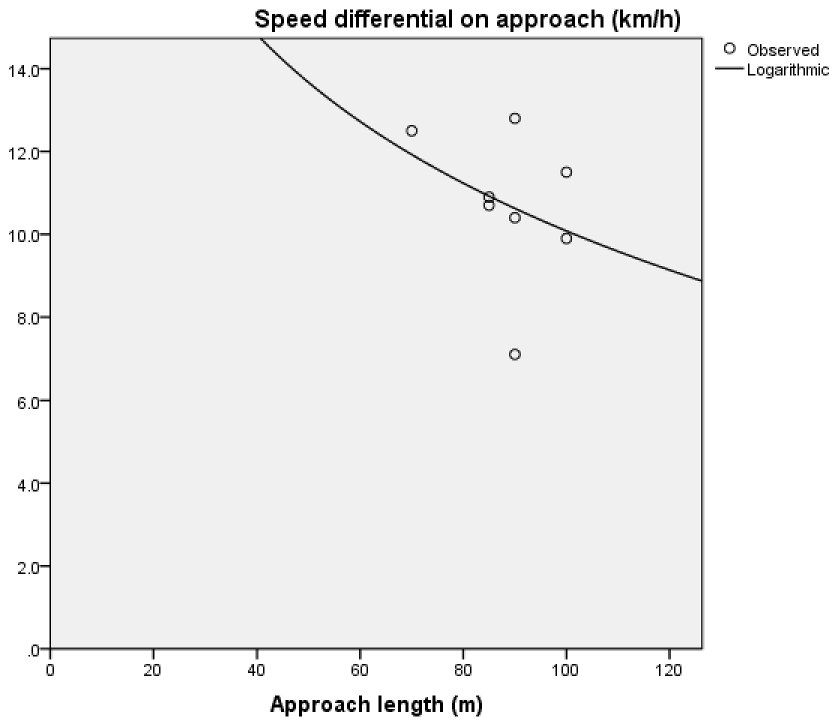
R	R Square	Adjusted R Square	Std. Error of the Estimate
.329	.108	-.041	1.809

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2.380	1	2.380	.727	.427
Residual	19.635	6	3.273		
Total	22.015	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Approach length (m))	-5.174	6.067	-.329	-.853	.427
(Constant)	33.906	27.192		1.247	.259



H-8 OUTPUTS FOR REGRESSION ANALYSIS USING LINEAR FUNCTION TO RELATE SPEED DIFFERENTIAL ON THE APPROACH TO APPROACH LENGTH (SPEED TABLES)

Model Summary (85th Percentile Speed)

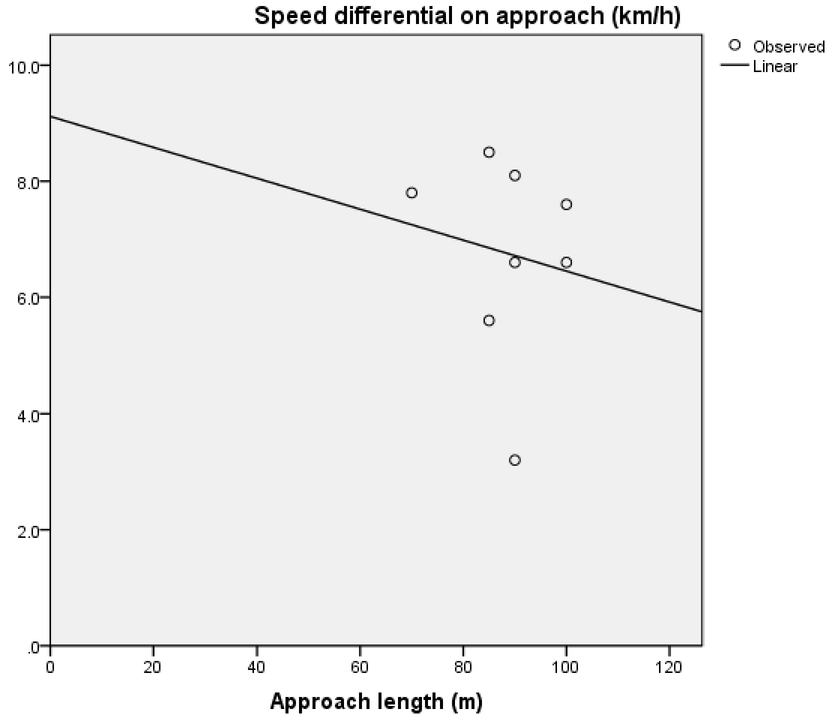
R	R Square	Adjusted R Square	Std. Error of the Estimate
.148	.022	-.141	1.836

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.453	1	.453	.134	.726
Residual	20.227	6	3.371		
Total	20.680	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Approach length (m)	-.027	.073	-.148	-.367	.726
(Constant)	9.117	6.486		1.406	.209



Model Summary (Mean Speed)

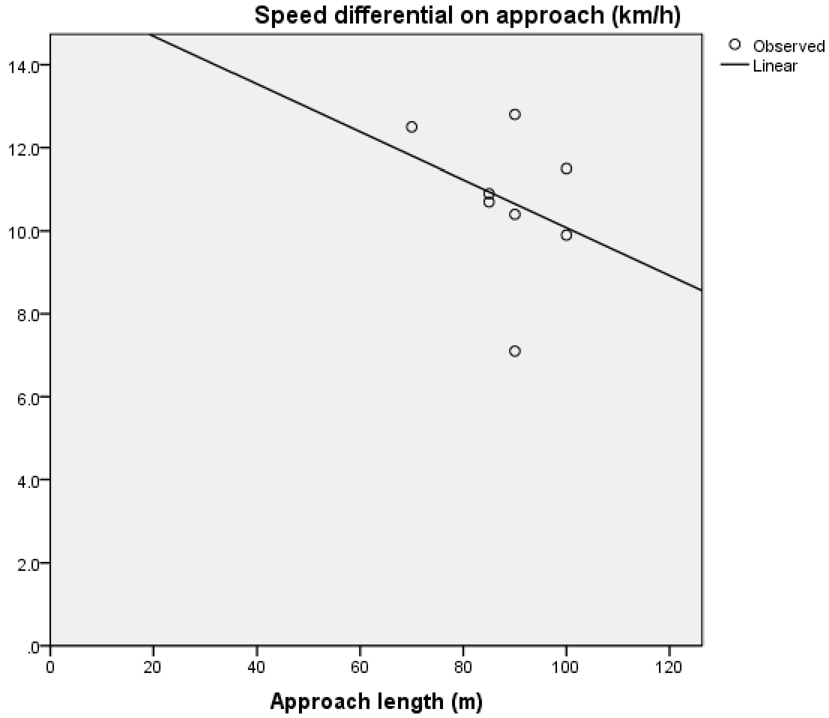
R	R Square	Adjusted R Square	Std. Error of the Estimate
.310	.096	-.054	1.821

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2.119	1	2.119	.639	.455
Residual	19.896	6	3.316		
Total	22.015	7			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Approach length (m)	-.058	.072	-.310	-.799	.455
(Constant)	15.841	6.433		2.462	.049



Appendix I

I-1 OUTPUTS FOR REGRESSION ANALYSIS USING S-CURVE FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN HUMPS TO SPACING BETWEEN HUMPS

Model Summary (85th Percentile Speed)

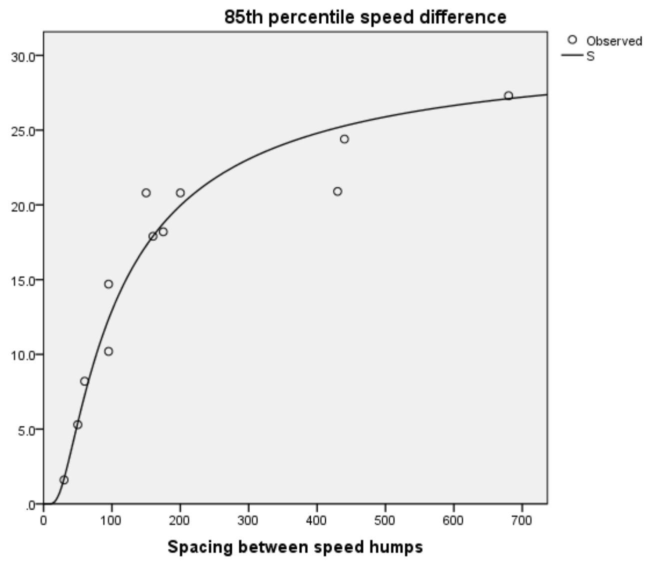
R	R Square	Adjusted R Square	Std. Error of the Estimate
.989	.978	.976	.126

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	7.148	1	7.148	446.900	.000
Residual	.160	10	.016		
Total	7.308	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Spacing between speed humps	-86.777	4.105	-.989	-21.140	.000
(Constant)	3.427	.055		62.170	.000



Model Summary (Mean Speed)

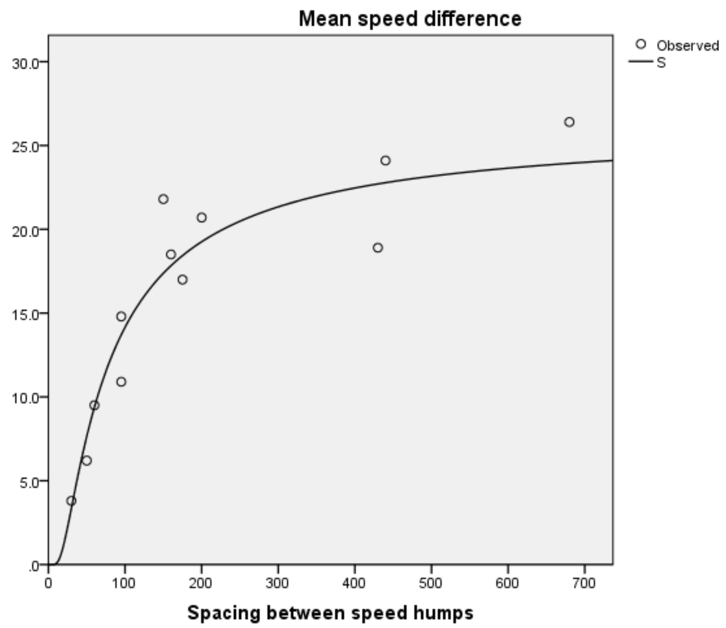
R	R Square	Adjusted R Square	Std. Error of the Estimate
.970	.940	.934	.151

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	3.603	1	3.603	157.934	.000
Residual	.228	10	.023		
Total	3.831	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Spacing between speed humps	-61.609	4.902	-.970	-12.567	.000
(Constant)	3.266	.066		49.605	.000



I-2 OUTPUTS FOR REGRESSION ANALYSIS USING POWER FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN HUMPS TO SPACING BETWEEN HUMPS

Model Summary (85th Percentile Speed)

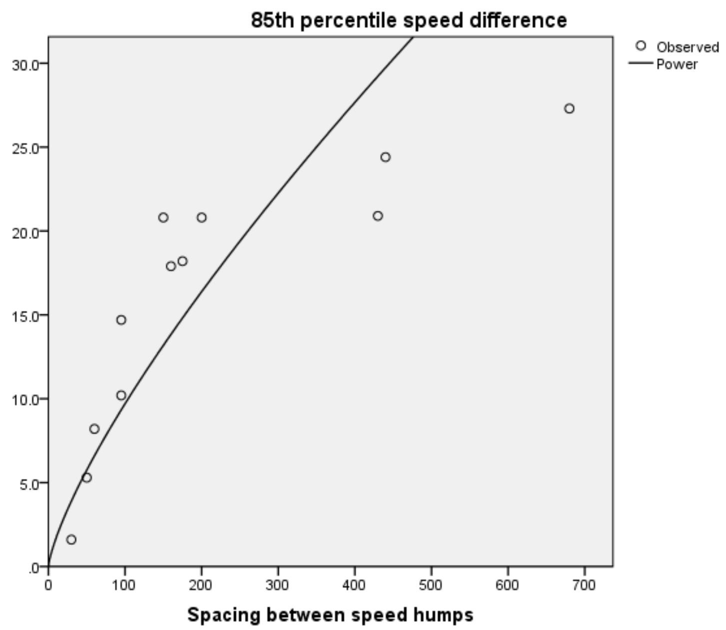
R	R Square	Adjusted R Square	Std. Error of the Estimate
.871	.759	.735	.420

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	5.547	1	5.547	31.497	.000
Residual	1.761	10	.176		
Total	7.308	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Spacing between speed humps)	.756	.135	.871	5.612	.000
(Constant)	.298	.203		1.467	.173



Model Summary (Mean Speed)

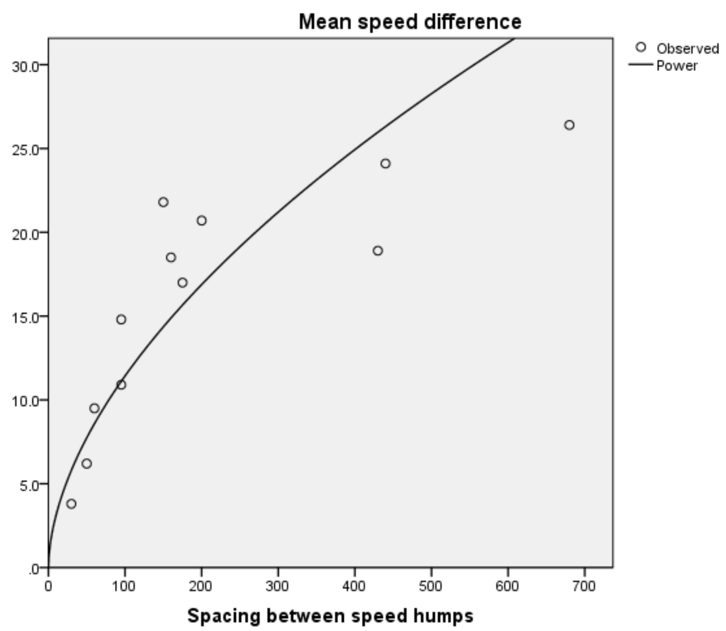
R	R Square	Adjusted R Square	Std. Error of the Estimate
.896	.802	.782	.275

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	3.073	1	3.073	40.489	.000
Residual	.759	10	.076		
Total	3.831	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Spacing between speed humps)	.563	.088	.896	6.363	.000
(Constant)	.856	.383		2.235	.049



I-3 OUTPUTS FOR REGRESSION ANALYSIS USING LOGARITHMIC FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN HUMPS TO SPACING BETWEEN HUMPS

Model Summary

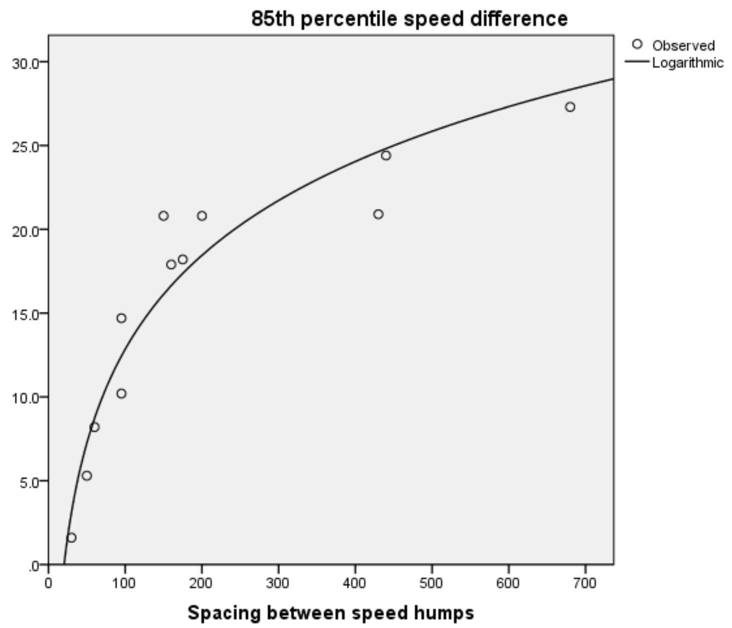
R	R Square	Adjusted R Square	Std. Error of the Estimate
.955	.912	.903	2.477

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	633.225	1	633.225	103.224	.000
Residual	61.345	10	6.134		
Total	694.569	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
ln(Spacing between speed humps)	8.078	.795	.955	10.160	.000
(Constant)	-24.355	4.022		-6.055	.000



Model Summary (Mean Speed)

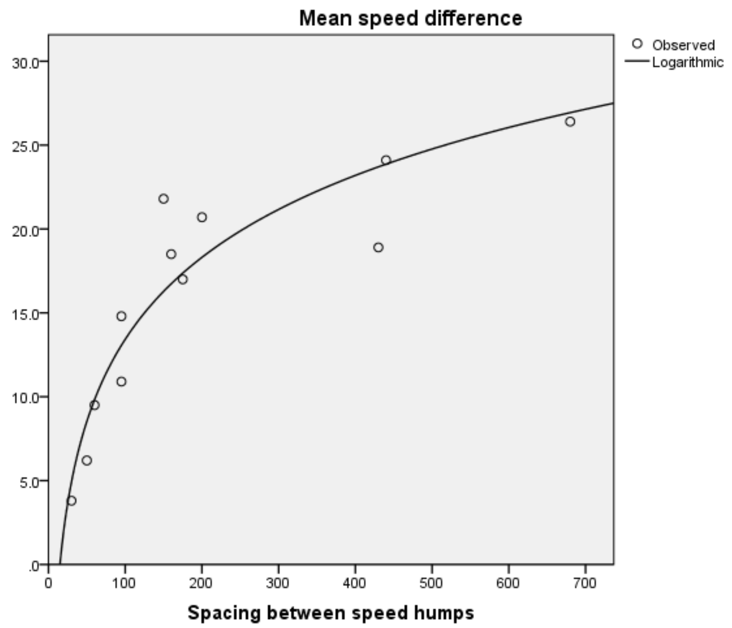
R	R Square	Adjusted R Square	Std. Error of the Estimate
.928	.862	.848	2.782

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	482.311	1	482.311	62.315	.000
Residual	77.399	10	7.740		
Total	559.710	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Spacing between speed humps)	7.050	.893	.928	7.894	.000
(Constant)	-19.046	4.518		-4.216	.002



I-4 OUTPUTS FOR REGRESSION ANALYSIS USING LINEAR FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN HUMPS TO SPACING BETWEEN HUMPS

Model Summary (85th Percentile Speed)

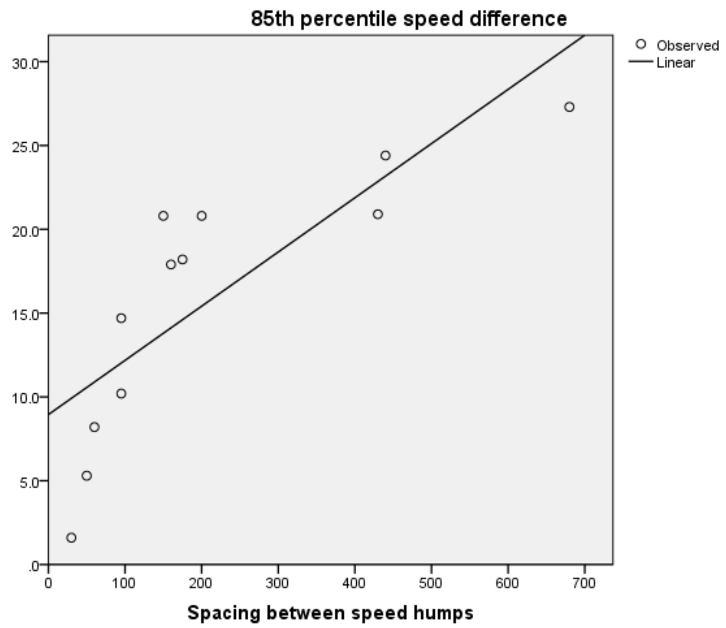
R	R Square	Adjusted R Square	Std. Error of the Estimate
.810	.657	.622	4.882

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	456.200	1	456.200	19.138	.001
Residual	238.369	10	23.837		
Total	694.569	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Spacing between speed humps	.032	.007	.810	4.375	.001
(Constant)	8.947	2.117		4.226	.002



Model Summary (Mean Speed)

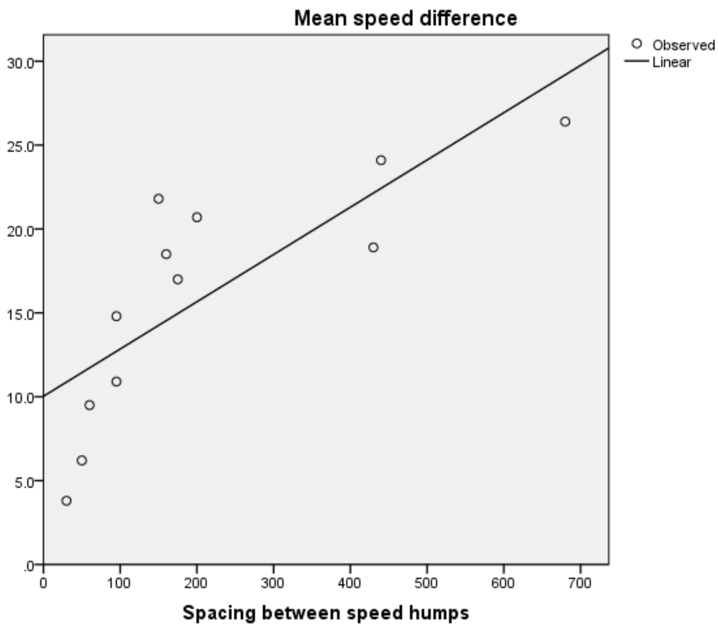
R	R Square	Adjusted R Square	Std. Error of the Estimate
.787	.619	.581	4.618

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	346.405	1	346.405	16.240	.002
Residual	213.305	10	21.331		
Total	559.710	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Spacing between speed humps	.028	.007	.787	4.030	.002
(Constant)	10.028	2.003		5.007	.001



I-5 OUTPUTS FOR REGRESSION ANALYSIS USING S-CURVE FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN TABLES TO SPACING BETWEEN TABLES

Model Summary (85th Percentile Speed)

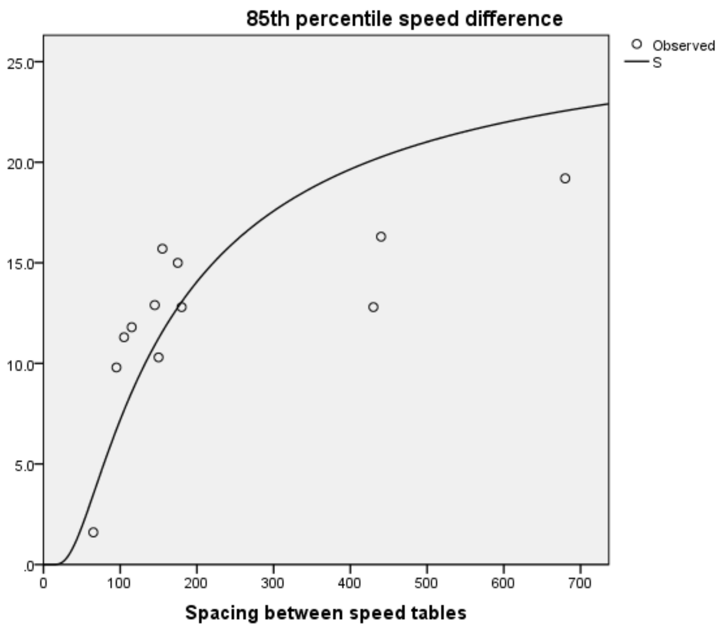
R	R Square	Adjusted R Square	Std. Error of the Estimate
.824	.680	.648	.380

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	3.058	1	3.058	21.222	.001
Residual	1.441	10	.144		
Total	4.499	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Spacing between speed tables	-133.964	29.080	-.824	-4.607	.001
(Constant)	3.313	.226		14.671	.000



Model Summary (Mean Speed)

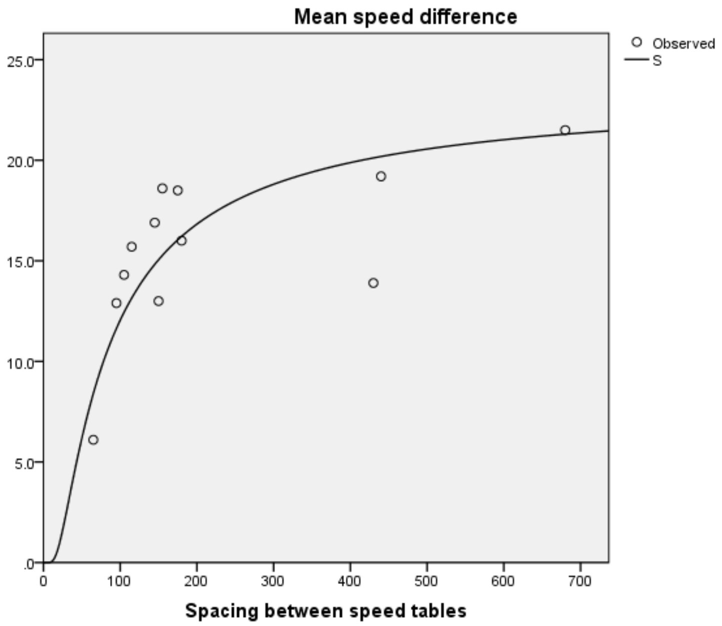
R	R Square	Adjusted R Square	Std. Error of the Estimate
.809	.654	.619	.201

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.760	1	.760	18.898	.001
Residual	.402	10	.040		
Total	1.162	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
1 / Spacing between speed tables	-66.778	15.361	-.809	-4.347	.001
(Constant)	3.157	.119		26.462	.000



I-6 OUTPUTS FOR REGRESSION ANALYSIS USING POWER FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN TABLES TO SPACING BETWEEN TABLES

Model Summary

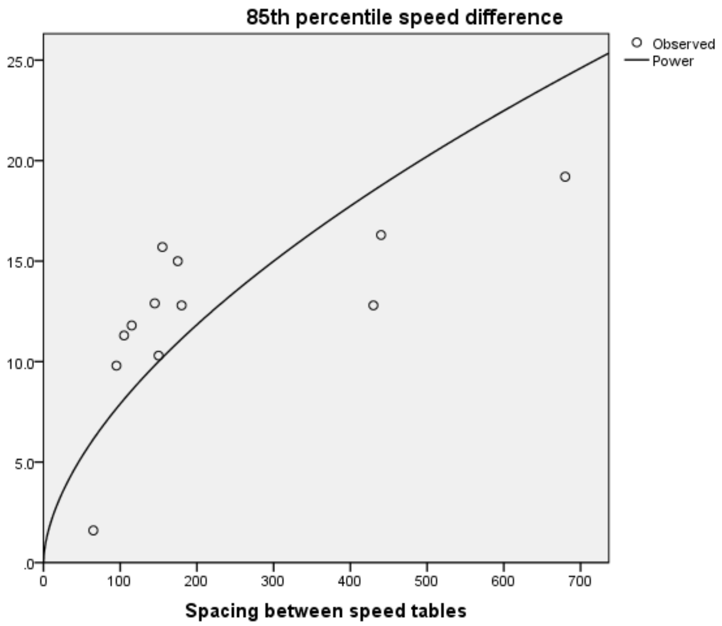
R	R Square	Adjusted R Square	Std. Error of the Estimate
.638	.407	.347	.517

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1.829	1	1.829	6.850	.026
Residual	2.670	10	.267		
Total	4.499	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Spacing between speed tables)	.584	.223	.638	2.617	.026
(Constant)	.536	.625		.858	.411



Model Summary (Mean Speed)

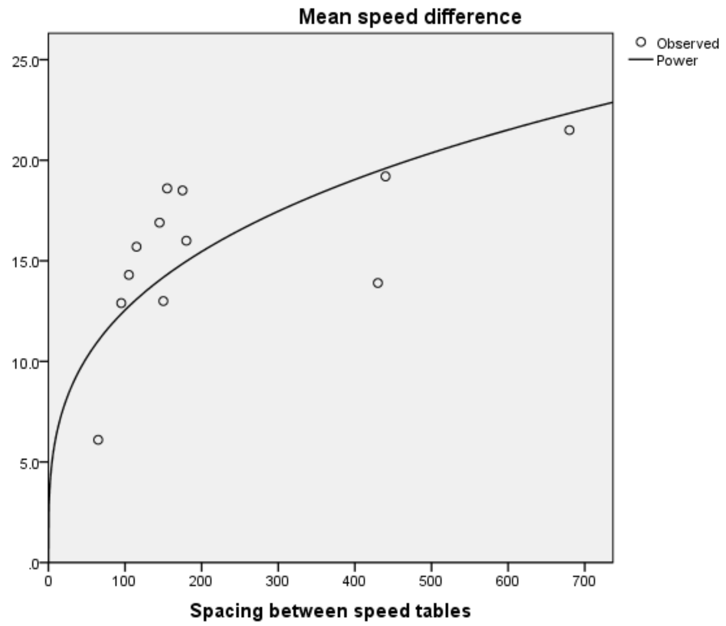
R	R Square	Adjusted R Square	Std. Error of the Estimate
.646	.417	.359	.260

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.485	1	.485	7.163	.023
Residual	.677	10	.068		
Total	1.162	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Spacing between speed tables)	.301	.112	.646	2.676	.023
(Constant)	3.142	1.845		1.703	.119



I-7 OUTPUTS FOR REGRESSION ANALYSIS USING LOGARITHMIC FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN TABLES TO SPACING BETWEEN TABLES

Model Summary (85th Percentile Speed)

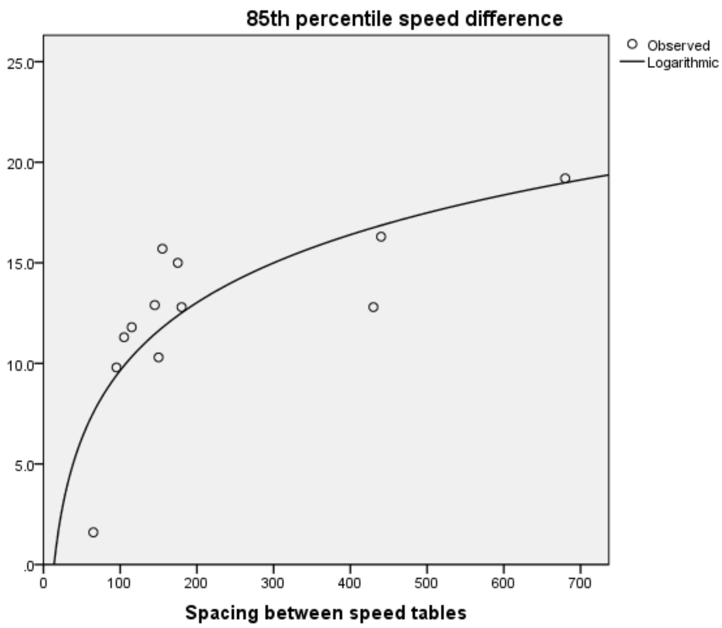
R	R Square	Adjusted R Square	Std. Error of the Estimate
.780	.608	.569	2.861

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	127.139	1	127.139	15.529	.003
Residual	81.870	10	8.187		
Total	209.009	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Spacing between speed tables)	4.869	1.236	.780	3.941	.003
(Constant)	-12.775	6.456		-1.979	.076



Model Summary (Mean Speed)

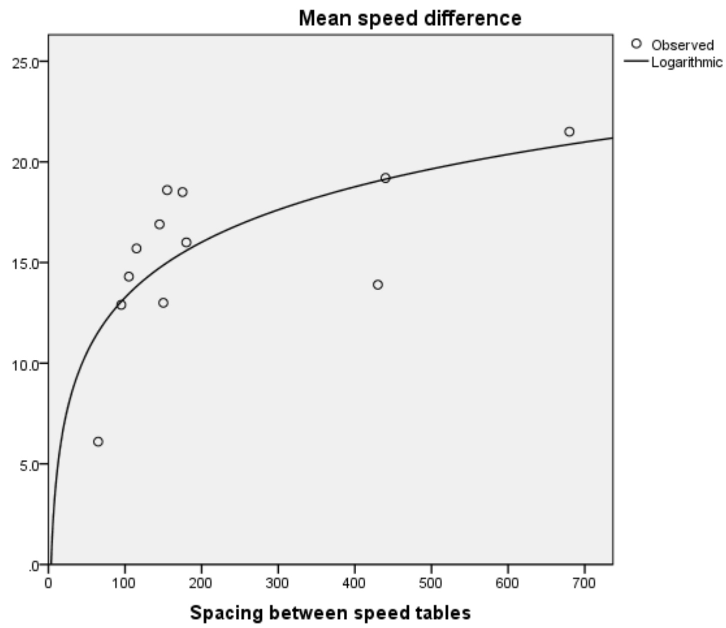
R	R Square	Adjusted R Square	Std. Error of the Estimate
.693	.481	.429	3.022

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	84.547	1	84.547	9.256	.012
Residual	91.343	10	9.134		
Total	175.890	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Spacing between speed tables)	3.971	1.305	.693	3.042	.012
(Constant)	-5.027	6.820		-.737	.478



I-8 OUTPUTS FOR REGRESSION ANALYSIS USING LINEAR FUNCTION TO RELATE SPEED DIFFERENTIAL BETWEEN TABLES TO SPACING BETWEEN TABLES

Model Summary (85th Percentile Speed)

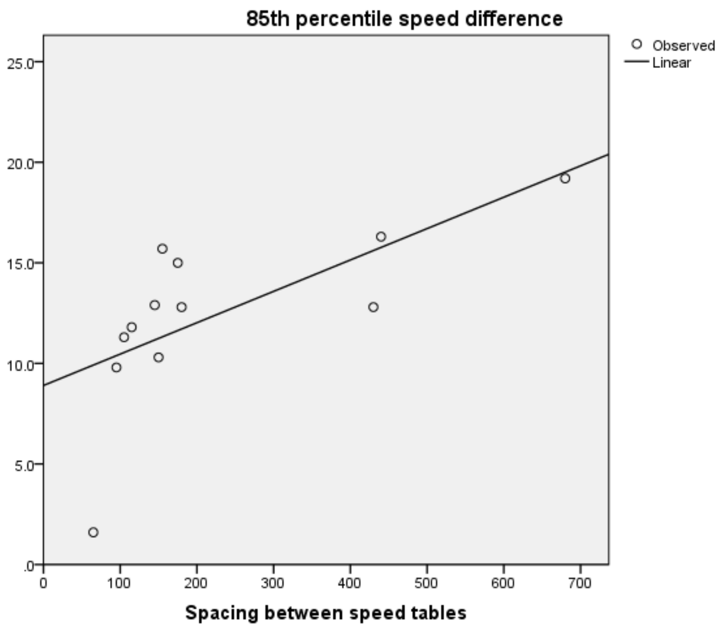
R	R Square	Adjusted R Square	Std. Error of the Estimate
.670	.449	.394	3.394

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	93.822	1	93.822	8.145	.017
Residual	115.188	10	11.519		
Total	209.009	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Spacing between speed tables	.016	.005	.670	2.854	.017
(Constant)	8.903	1.585		5.618	.000



Model Summary (Mean Speed)

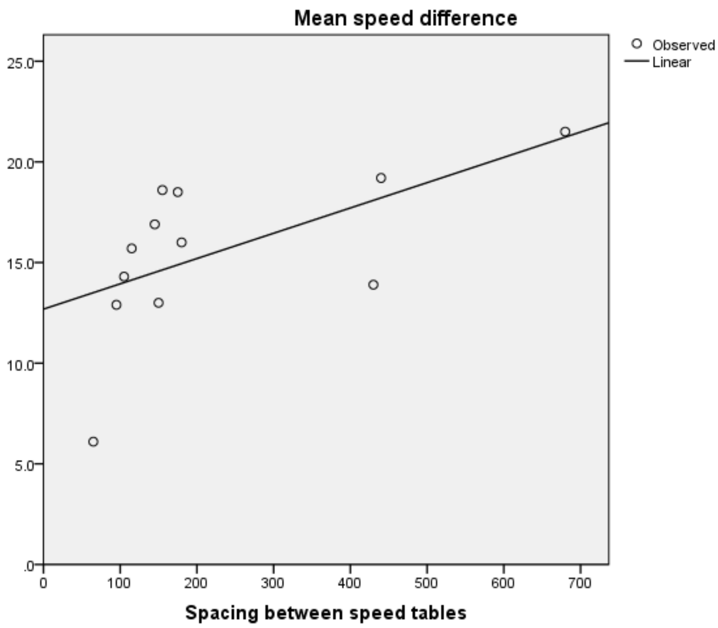
R	R Square	Adjusted R Square	Std. Error of the Estimate
.588	.346	.281	3.391

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	60.892	1	60.892	5.295	.044
Residual	114.998	10	11.500		
Total	175.890	11			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Spacing between speed tables	.013	.005	.588	2.301	.044
(Constant)	12.686	1.583		8.011	.000



Appendix J

J-1 NUMBER OF INTERSECTION CRASHES AT THE SURVEYED STREETS BEFORE AND AFTER TRAFFIC CALMING

No.	Street	No. of intersection crashes		Period (years)	No. of intersection crashes/year	
		Before	After		Before	After
1	Aylesford Street	3	2	3	1.00	0.67
2	Francis Avenue	1	2	3	0.33	0.67
3	Stratford Street	4	1	6	0.67	0.17
4	Snowdon Road	1	1	5	0.20	0.20
5	Hamilton Avenue	1	1	3	0.33	0.33
6	Burke Street	0	1	3	0.00	0.33
7	Rattray Street	0	0	2	0.00	0.00
8	Kirkwood Avenue	3	2	3	1.00	0.67
9	Randolph Street	2	2	3	0.67	0.67
10	Mackenzie Avenue	4	1	2	2.00	0.50
11	Perry Street	0	0	3	0.00	0.00
12	Barbour Street	0	0	3	0.00	0.00
13	Grafton Street	1	1	2	0.50	0.50
14	Grenville Street	1	1	4	0.25	0.25
15	Baretta Street	0	1	4	0.00	0.25
16	Carrick Street	0	0	3	0.00	0.00
17	Flockton Street	0	3	3	0.00	1.00
18	Fairfield Avenue	2	2	3	0.67	0.67
19	Wherstead Road	0	0	6	0.00	0.00
20	Webb Street	1	0	6	0.17	0.00
21	Geraldine Street	4	2	6	0.67	0.33
22	Saltaire Street	3	2	4	0.75	0.50
23	Merivale Lane	4	5	7	0.57	0.71
24	Mary Street	9	6	6	1.50	1.00
25	Grants Road	8	4	6	1.33	0.67
26	Glenroy Street	3	1	3	1.00	0.33
27	Hastings Street	7	10	5	1.40	2.00
28	Wildberry Street	0	4	5	0.00	0.80
		62	55	112		
	Crashes/year/street	0.55	0.49			

J-2 NUMBER OF MID-BLOCK CRASHES AT THE SURVEYED STREETS BEFORE AND AFTER TRAFFIC CALMING

No.	Street	No. of mid-block crashes		Period (years)	No. of mid-block crashes/year	
		Before	After		Before	After
1	Aylesford Street	3	3	3	1.00	1.00
2	Francis Avenue	0	1	3	0.00	0.33
3	Stratford Street	0	1	6	0.00	0.17
4	Snowdon Road	0	0	5	0.00	0.00
5	Hamilton Avenue	2	2	3	0.67	0.67
6	Burke Street	0	1	3	0.00	0.33
7	Rattray Street	0	0	2	0.00	0.00
8	Kirkwood Avenue	1	1	3	0.33	0.33
9	Randolph Street	0	1	3	0.00	0.33
10	Mackenzie Avenue	0	2	2	0.00	1.00
11	Perry Street	0	0	3	0.00	0.00
12	Barbour Street	0	0	3	0.00	0.00
13	Grafton Street	1	0	2	0.50	0.00
14	Grenville Street	0	1	4	0.00	0.25
15	Baretta Street	1	0	4	0.25	0.00
16	Carrick Street	0	0	3	0.00	0.00
17	Flockton Street	1	0	3	0.33	0.00
18	Fairfield Avenue	1	1	3	0.33	0.33
19	Wherstead Road	0	0	6	0.00	0.00
20	Webb Street	0	0	6	0.00	0.00
21	Geraldine Street	1	2	6	0.17	0.33
22	Saltaire Street	0	0	4	0.00	0.00
23	Merivale Lane	0	1	7	0.00	0.14
24	Mary Street	1	0	6	0.17	0.00
25	Grants Road	1	1	6	0.17	0.17
26	Glenroy Street	0	0	3	0.00	0.00
27	Hastings Street	3	3	5	0.60	0.60
28	Wildberry Street	1	0	5	0.20	0.00
		17	21	112		
	Crashes/year/street	0.15	0.19			

J-3 NUMBER OF STREET-END CRASHES AT THE SURVEYED STREETS BEFORE AND AFTER TRAFFIC CALMING

No.	Street	No. of street-end crashes		Period (years)	No. of street-end crashes/year	
		Before	After		Before	After
1	Aylesford Street	2	2	3	0.67	0.67
2	Francis Avenue	1	2	3	0.33	0.67
3	Stratford Street	4	1	6	0.67	0.17
4	Snowdon Road	1	1	5	0.20	0.20
5	Hamilton Avenue	0	0	3	0.00	0.00
6	Burke Street	0	1	3	0.00	0.33
7	Rattray Street	0	0	2	0.00	0.00
8	Kirkwood Avenue	3	2	3	1.00	0.67
9	Randolph Street	0	0	3	0.00	0.00
10	Mackenzie Avenue	2	1	2	1.00	0.50
11	Perry Street	0	0	3	0.00	0.00
12	Barbour Street	0	0	3	0.00	0.00
13	Grafton Street	0	0	2	0.00	0.00
14	Grenville Street	0	0	4	0.00	0.00
15	Baretta Street	0	1	4	0.00	0.25
16	Carrick Street	0	0	3	0.00	0.00
17	Flockton Street	0	1	3	0.00	0.33
18	Fairfield Avenue	2	2	3	0.67	0.67
19	Wherstead Road	0	0	6	0.00	0.00
20	Webb Street	1	0	6	0.17	0.00
21	Geraldine Street	2	0	6	0.33	0.00
22	Saltaire Street	3	2	4	0.75	0.50
23	Merivale Lane	3	4	7	0.43	0.57
24	Mary Street	7	4	6	1.17	0.67
25	Grants Road	6	3	6	1.00	0.50
26	Glenroy Street	1	0	3	0.33	0.00
27	Hastings Street	3	2	5	0.60	0.40
28	Wildberry Street	0	0	5	0.00	0.00
		41	29	112		
	Crashes/year/street	0.37	0.26			

J-4 NUMBER OF SIDE ROAD CRASHES AT THE SURVEYED STREETS BEFORE AND AFTER TRAFFIC CALMING

No.	Road	No. of side road crashes		Period (years)	No. of side road crashes/year	
		Before	After		Before	After
1	Aylesford Street	1	0	3	0.33	0.00
2	Francis Avenue	0	0	3	0.00	0.00
3	Stratford Street	0	0	6	0.00	0.00
4	Snowdon Road	0	0	5	0.00	0.00
5	Hamilton Avenue	1	1	3	0.33	0.33
6	Burke Street	0	0	3	0.00	0.00
7	Rattray Street	0	0	2	0.00	0.00
8	Kirkwood Avenue	0	0	3	0.00	0.00
9	Randolph Street	2	2	3	0.67	0.67
10	Mackenzie Avenue	2	0	2	1.00	0.00
11	Perry Street	0	0	3	0.00	0.00
12	Barbour Street	0	0	3	0.00	0.00
13	Grafton Street	1	1	2	0.50	0.50
14	Grenville Street	1	1	4	0.25	0.25
15	Baretta Street	0	0	4	0.00	0.00
16	Carrick Street	0	0	3	0.00	0.00
17	Flockton Street	0	2	3	0.00	0.67
18	Fairfield Avenue	0	0	3	0.00	0.00
19	Wherstead Road	0	0	6	0.00	0.00
20	Webb Street	0	0	6	0.00	0.00
21	Geraldine Street	2	2	6	0.33	0.33
22	Saltaire Street	0	0	4	0.00	0.00
23	Merivale Lane	1	1	7	0.14	0.14
24	Mary Street	2	2	6	0.33	0.33
25	Grants Road	2	1	6	0.33	0.17
26	Glenroy Street	2	1	3	0.67	0.33
27	Hastings Street	4	8	5	0.80	1.60
28	Wildberry Street	0	4	5	0.00	0.80
		21	26	112		
	Crashes/year/street	0.19	0.23			

Appendix K

K-1 LIKELIHOOD OF A FACTOR BEING CITED FOR A CRASH ON A STREET BEFORE TRAFFIC CALMING

No	Road	Crash Factors															
		Alcohol	Too Fast	Failed To Giveway or Stop	Failed To Keep Left	Incorrect Lane or Position	Overtaking	Poor Handling	Poor Observation	Poor Judgement	Fatigue	Weather	Road Factors	Vehicle Factors	Pedestrian Factors	Disabled or Old or Ill	Other
1	Aylesford Street	2	2	1	0	2	0	3	1	1	0	2	0	0	0	0	0
2	Francis Avenue	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0
3	Stratford Street	0	0	3	0	0	1	0	1	1	0	1	0	0	0	0	0
4	Snowdon Road	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
5	Hamilton Avenue	2	1	0	0	1	0	0	0	0	1	0	0	0	0	0	0
6	Burke Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	Rattray Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Kirkwood Avenue	1	1	2	0	1	0	0	1	0	0	0	0	0	0	0	0
9	Randolph Street	0	1	2	0	0	0	0	1	0	0	0	0	0	0	0	0
10	Mackenzie Avenue	0	1	2	0	0	0	2	2	0	0	0	0	0	0	1	0
11	Perry Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Barbour Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Grafton Street	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
14	Grenville Street	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0
15	Baretta Street	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
16	Carrick Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Flockton Street	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	Fairfield Avenue	1	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0
19	Wherstead Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Webb Street	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0

No	Road	Crash Factors															
		Alcohol	**Too Fast**	**Failed To Giveway or Stop**	**Failed To Keep Left**	**Incorrect Lane or Position**	**Overtaking**	**Poor Handling**	**Poor Observation**	**Poor Judgement**	**Fatigue**	**Weather**	**Road Factors**	**Vehicle Factors**	**Pedestrian Factors**	**Disabled or Old or Ill**	**Other**
21	Geraldine Street	1	0	2	1	2	0	0	1	0	0	0	0	0	0	0	0
22	Saltaire Street	0	0	1	0	1	0	0	3	0	0	2	0	0	0	0	0
23	Merivale Lane	0	1	0	1	0	0	0	1	0	0	0	0	0	0	0	0
24	Mary Street	0	0	4	0	0	1	0	6	1	0	0	1	0	1	0	0
25	Grants Road	1	1	5	0	2	0	0	6	0	0	0	0	0	0	0	1
26	Glenroy Street	0	1	2	0	0	0	0	1	0	0	0	0	1	0	0	0
27	Hastings Street	1	0	4	0	0	0	2	6	0	0	0	0	0	0	0	2
28	Wildberry Street	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
	Total	**12**	**11**	**31**	**3**	**10**	**5**	**9**	**33**	**3**	**1**	**5**	**1**	**1**	**1**	**1**	**5**
	Citing/crash/street	**0.15**	**0.14**	**0.39**	**0.04**	**0.13**	**0.06**	**0.11**	**0.42**	**0.04**	**0.01**	**0.06**	**0.01**	**0.01**	**0.01**	**0.01**	**0.06**

K-2 LIKELIHOOD OF A FACTOR BEING CITED FOR A CRASH ON A STREET AFTER TRAFFIC CALMING

No	Road	Crash Factors															
		Alcohol	Too Fast	Failed To Giveway or Stop	Failed To Keep Left	Incorrect Lane or Position	Overtaking	Poor Handling	Poor Observation	Poor Judgement	Fatigue	Weather	Road Factors	Vehicle Factors	Pedestrian Factors	Disabled or Old or Ill	Other
1	Aylesford Street	2	1	0	0	0	1	2	1	0	0	0	1	0	0	0	1
2	Francis Avenue	0	1	1	0	1	0	1	1	1	0	0	0	0	0	0	1
3	Stratford Street	0	0	0	0	1	1	0	2	1	0	0	0	0	0	0	0
4	Snowdon Road	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
5	Hamilton Avenue	1	0	1	0	1	0	0	1	2	1	1	0	0	0	0	0
6	Burke Street	1	0	1	0	1	0	0	1	0	0	0	0	0	0	0	0
7	Rattray Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Kirkwood Avenue	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0
9	Randolph Street	1	1	2	0	1	0	0	0	0	0	0	0	1	1	0	0
10	Mackenzie Avenue	1	0	0	0	0	0	1	2	1	0	0	0	0	0	0	1
11	Perry Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	Barbour Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Grafton Street	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1
14	Grenville Street	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0	0
15	Baretta Street	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
16	Carrick Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Flockton Street	2	0	1	0	0	0	1	1	0	0	0	0	0	0	1	0
18	Fairfield Avenue	2	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0
19	Wherstead Road	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	Webb Street	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	Geraldine Street	0	1	2	0	0	0	0	2	0	0	0	0	0	0	0	1
22	Saltaire Street	0	0	1	0	0	0	0	2	0	0	0	1	0	0	0	0
23	Merivale Lane	0	0	4	0	0	0	4	0	0	0	0	0	0	1	0	0
24	Mary Street	1	0	5	0	0	0	1	5	0	0	0	0	0	0	0	0

No	Road	Crash Factors															
		Alcohol	Too Fast	Failed To Giveway or Stop	Failed To Keep Left	Incorrect Lane or Position	Overtaking	Poor Handling	Poor Observation	Poor Judgement	Fatigue	Weather	Road Factors	Vehicle Factors	Pedestrian Factors	Disabled or Old or Ill	Other
25	Grants Road	0	0	4	0	1	0	0	3	0	0	0	0	0	0	0	0
26	Glenroy Street	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
27	Hastings Street	1	1	5	1	0	0	2	9	2	0	2	0	0	0	0	1
28	Wildberry Street	0	0	4	0	0	0	0	3	0	0	0	0	0	0	0	0
	Total	**13**	**5**	**33**	**1**	**8**	**2**	**16**	**37**	**9**	**1**	**3**	**3**	**1**	**2**	**1**	**6**
	Citing/crash/street	**0.17**	**0.07**	**0.43**	**0.01**	**0.11**	**0.03**	**0.21**	**0.49**	**0.12**	**0.01**	**0.04**	**0.04**	**0.01**	**0.03**	**0.01**	**0.08**

Appendix L

L-1 OUTPUTS FOR REGRESSION ANALYSIS USING POWER FUNCTION TO ESTIMATE CURVE FOR NOISE–SPEED RELATIONSHIP ACROSS 75 MM SPEED HUMP

Model Summary (Nearside Lane)

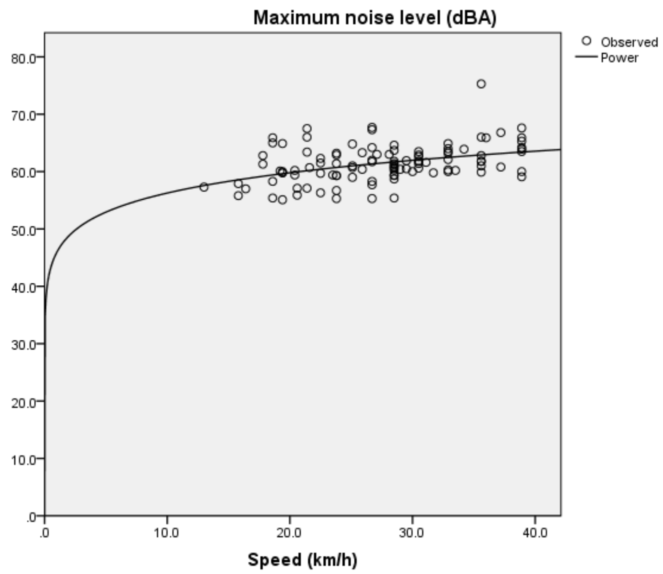
R	R Square	Adjusted R Square	Std. Error of the Estimate
.407	.166	.158	.048

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.048	1	.048	20.635	.000
Residual	.244	104	.002		
Total	.292	105			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Speed (km/h))	.088	.019	.407	4.543	.000
(Constant)	45.946	2.930		15.681	.000



Model Summary (Farside Lane)

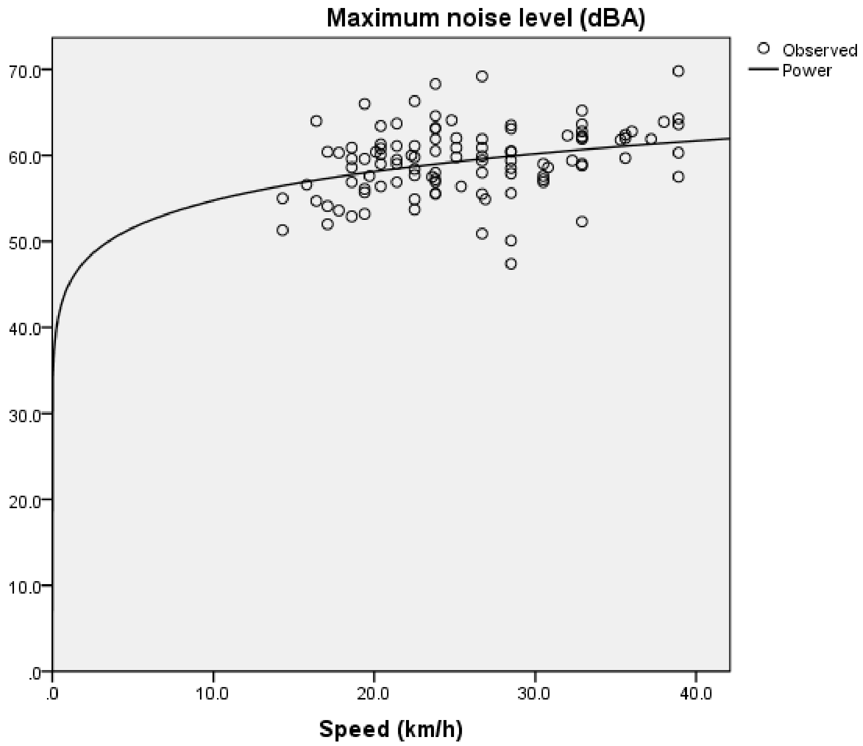
R	R Square	Adjusted R Square	Std. Error of the Estimate
.311	.097	.088	.065

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.047	1	.047	11.014	.001
Residual	.442	103	.004		
Total	.489	104			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Speed (km/h))	.086	.026	.311	3.319	.001
(Constant)	44.895	3.761		11.939	.000



L-2 OUTPUTS FOR REGRESSION ANALYSIS USING POWER FUNCTION TO ESTIMATE CURVE FOR NOISE–SPEED RELATIONSHIP ACROSS 100 MM SPEED

Model Summary (Nearside Lane)

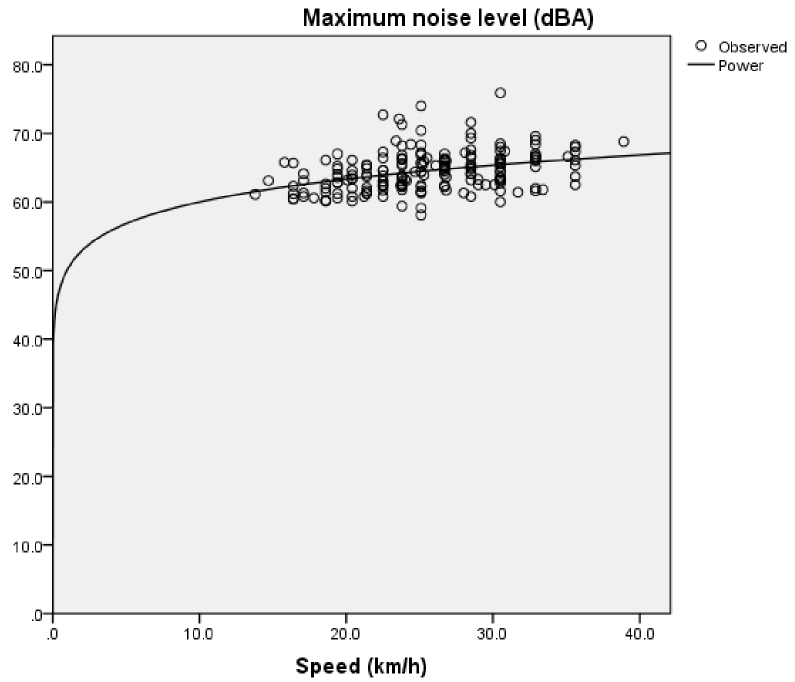
R	R Square	Adjusted R Square	Std. Error of the Estimate
.364	.132	.128	.041

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.048	1	.048	28.356	.000
Residual	.318	186	.002		
Total	.366	187			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Speed (km/h))	.078	.015	.364	5.325	.000
(Constant)	50.120	2.367		21.172	.000



Model Summary (Farside Lane)

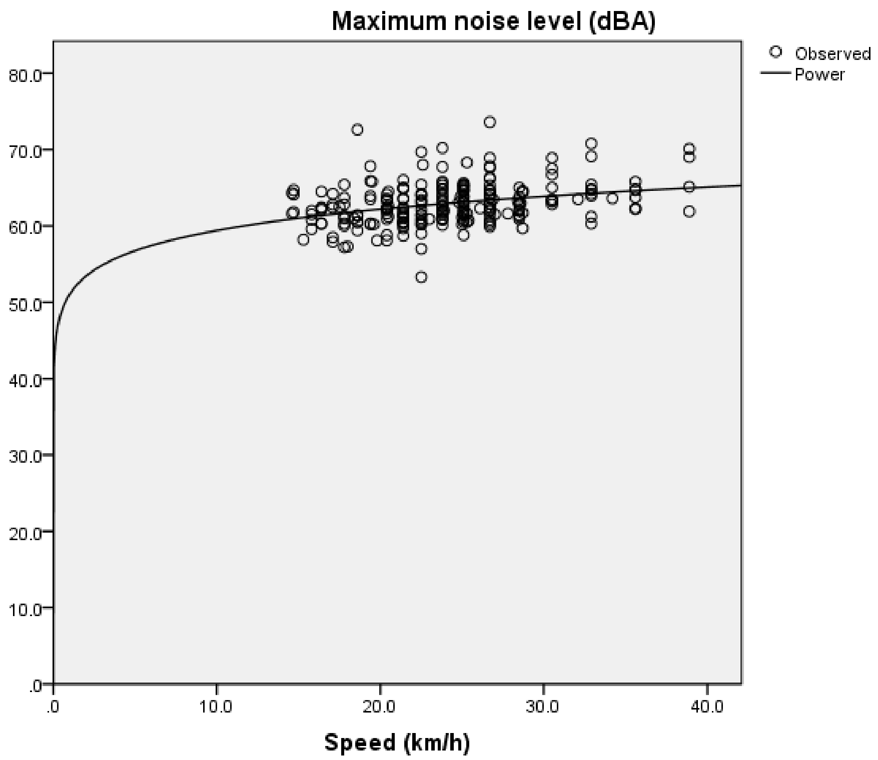
R	R Square	Adjusted R Square	Std. Error of the Estimate
.323	.105	.101	.041

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.044	1	.044	26.274	.000
Residual	.381	225	.002		
Total	.425	226			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Speed (km/h))	.066	.013	.323	5.126	.000
(Constant)	51.019	2.079		24.546	.000



L-3 OUTPUTS FOR REGRESSION ANALYSIS USING POWER FUNCTION TO ESTIMATE CURVE FOR NOISE–SPEED RELATIONSHIP ACROSS FLAT SECTION OF ROAD

Model Summary (Nearside Lane)

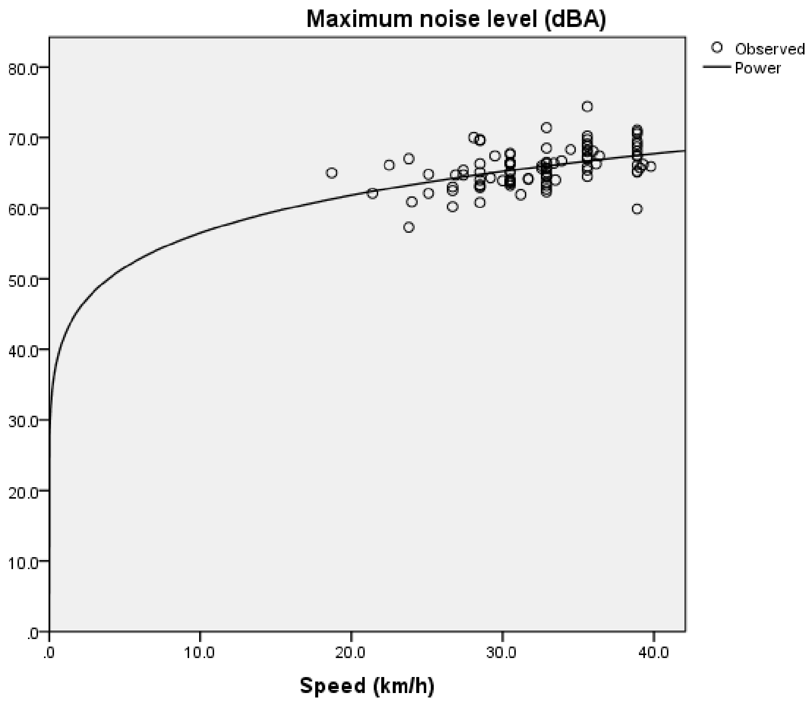
R	R Square	Adjusted R Square	Std. Error of the Estimate
.463	.215	.206	.038

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.037	1	.037	25.687	.000
Residual	.135	94	.001		
Total	.172	95			

Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Speed (km/h))	.131	.026	.463	5.068	.000
(Constant)	41.805	3.736		11.190	.000



Model Summary (Farside Lane)

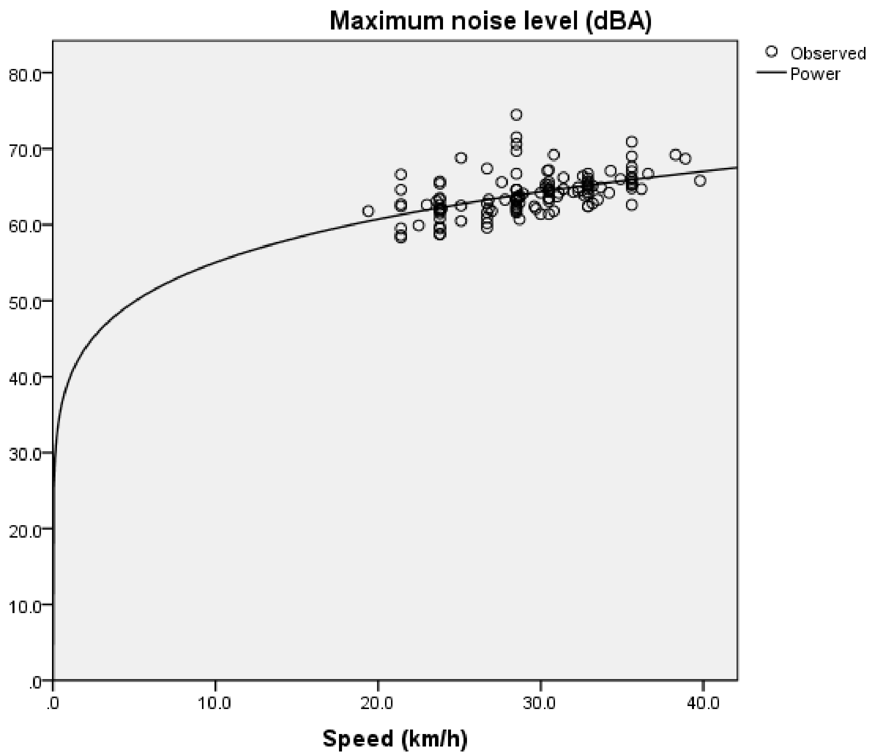
R	R Square	Adjusted R Square	Std. Error of the Estimate
.518	.268	.262	.036

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	.061	1	.061	46.137	.000
Residual	.167	126	.001		
Total	.228	127			

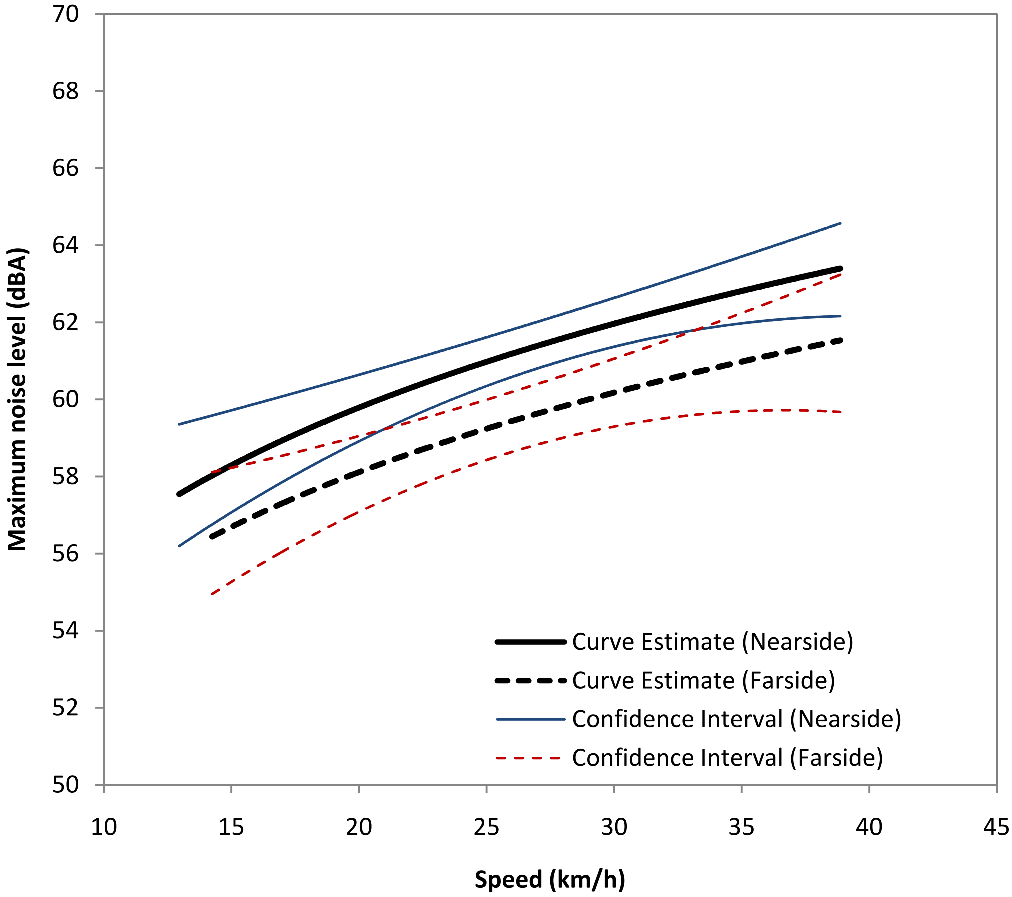
Coefficients

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
ln(Speed (km/h))	.142	.021	.518	6.792	.000
(Constant)	39.659	2.800		14.163	.000



Appendix M

M-1 CONFIDENCE INTERVALS FOR THE CURVE ESTIMATES OF NOISE–SPEED RELATIONSHIPS ACROSS 75 MM SPEED HUMP

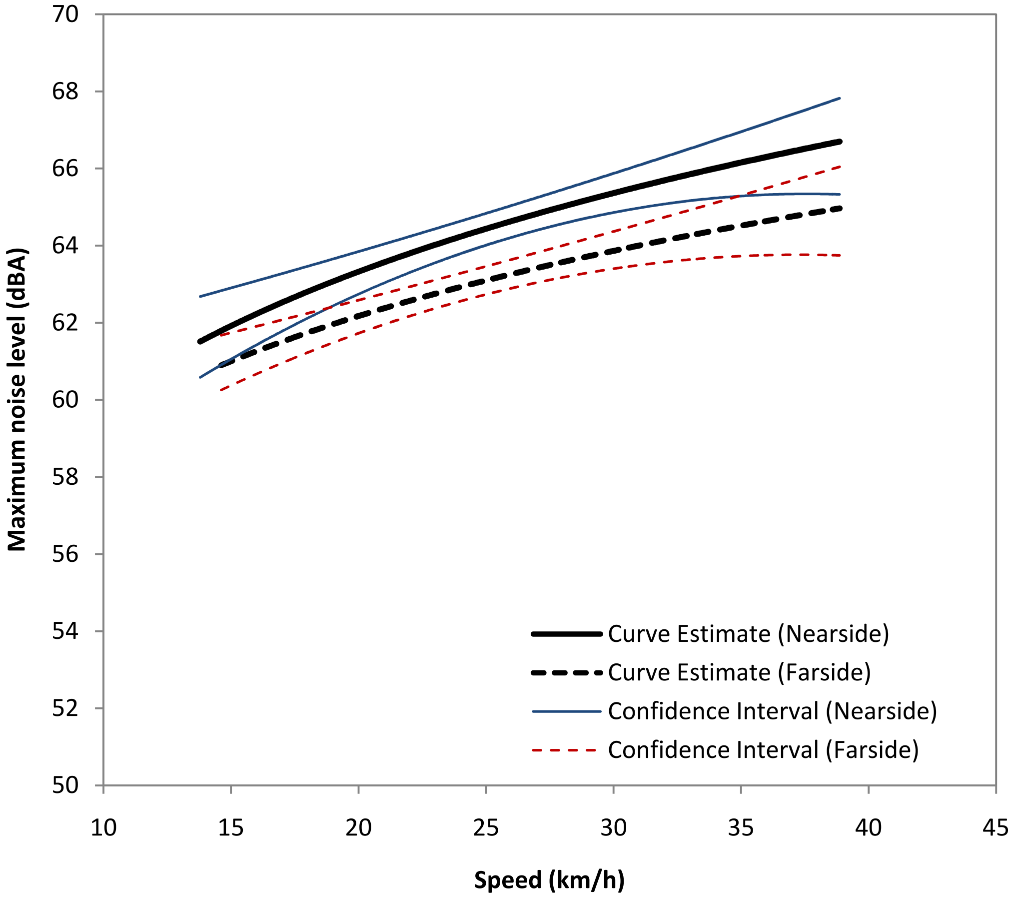


No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
1	57.3	13.0	57.56	1.4403	56.1223	59.0030
2	57.9	15.8	58.59	1.2053	57.3829	59.7935
3	55.8	15.8	58.59	1.2053	57.3829	59.7935
4	57.0	16.4	58.78	1.1570	57.6261	59.9401
5	62.8	17.8	59.20	1.0510	58.1476	60.2496
6	61.3	17.8	59.20	1.0510	58.1476	60.2496
7	65.0	18.6	59.42	0.9930	58.4277	60.4138
8	58.3	18.6	59.42	0.9930	58.4277	60.4138
9	55.4	18.6	59.42	0.9930	58.4277	60.4138
10	65.9	18.6	59.42	0.9930	58.4277	60.4138
11	60.1	19.2	59.59	0.9473	58.6470	60.5417
12	60.0	19.4	59.65	0.9317	58.7219	60.5853
13	59.8	19.4	59.65	0.9317	58.7219	60.5853
14	64.9	19.4	59.65	0.9317	58.7219	60.5853
15	55.1	19.4	59.65	0.9317	58.7219	60.5853
16	59.8	19.4	59.65	0.9317	58.7219	60.5853
17	59.4	20.4	59.90	0.8674	59.0310	60.7657

No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
18	60.2	20.4	59.90	0.8674	59.0310	60.7657
19	55.9	20.6	59.96	0.8509	59.1106	60.8124
20	57.1	20.6	59.96	0.8509	59.1106	60.8124
21	63.4	21.4	60.16	0.8008	59.3552	60.9569
22	67.5	21.4	60.16	0.8008	59.3552	60.9569
23	66.0	21.4	60.16	0.8008	59.3552	60.9569
24	57.1	21.4	60.16	0.8008	59.3552	60.9569
25	60.7	21.6	60.21	0.7883	59.4177	60.9942
26	62.3	22.5	60.43	0.7339	59.6943	61.1621
27	56.3	22.5	60.43	0.7339	59.6943	61.1621
28	59.7	22.5	60.43	0.7339	59.6943	61.1621
29	61.5	22.5	60.43	0.7339	59.6943	61.1621
30	59.4	23.5	60.65	0.6835	59.9684	61.3354
31	62.9	23.8	60.72	0.6701	60.0463	61.3865
32	59.3	23.8	60.72	0.6701	60.0463	61.3865
33	56.7	23.8	60.72	0.6701	60.0463	61.3865
34	59.3	23.8	60.72	0.6701	60.0463	61.3865
35	63.2	23.8	60.72	0.6701	60.0463	61.3865
36	55.3	23.8	60.72	0.6701	60.0463	61.3865
37	61.4	23.8	60.72	0.6701	60.0463	61.3865
38	61.0	25.1	61.02	0.6160	60.4066	61.6385
39	59.0	25.1	61.02	0.6160	60.4066	61.6385
40	64.8	25.1	61.02	0.6160	60.4066	61.6385
41	60.7	25.1	61.02	0.6160	60.4066	61.6385
42	63.3	25.9	61.18	0.5958	60.5873	61.7789
43	60.4	25.9	61.18	0.5958	60.5873	61.7789
44	55.3	26.7	61.35	0.5828	60.7662	61.9318
45	62.0	26.7	61.35	0.5828	60.7662	61.9318
46	58.3	26.7	61.35	0.5828	60.7662	61.9318
47	67.7	26.7	61.35	0.5828	60.7662	61.9318
48	64.2	26.7	61.35	0.5828	60.7662	61.9318
49	61.7	26.7	61.35	0.5828	60.7662	61.9318
50	57.7	26.7	61.35	0.5828	60.7662	61.9318
51	67.3	26.7	61.35	0.5828	60.7662	61.9318
52	63.0	27.1	61.43	0.5796	60.8545	62.0137
53	63.0	28.1	61.63	0.5822	61.0488	62.2132
54	60.9	28.5	61.70	0.5865	61.1119	62.2849
55	61.2	28.5	61.70	0.5865	61.1119	62.2849
56	63.7	28.5	61.70	0.5865	61.1119	62.2849
57	58.7	28.5	61.70	0.5865	61.1119	62.2849
58	61.4	28.5	61.70	0.5865	61.1119	62.2849
59	59.3	28.5	61.70	0.5865	61.1119	62.2849
60	60.2	28.5	61.70	0.5865	61.1119	62.2849
61	64.6	28.5	61.70	0.5865	61.1119	62.2849
62	60.5	28.5	61.70	0.5865	61.1119	62.2849
63	60.7	28.5	61.70	0.5865	61.1119	62.2849
64	61.8	28.5	61.70	0.5865	61.1119	62.2849
65	59.4	28.5	61.70	0.5865	61.1119	62.2849
66	55.4	28.5	61.70	0.5865	61.1119	62.2849
67	60.4	29.0	61.79	0.5951	61.1946	62.3849
68	60.5	29.5	61.88	0.6073	61.2755	62.4900
69	61.9	29.5	61.88	0.6073	61.2755	62.4900
70	60.0	30.0	61.98	0.6231	61.3544	62.6007
71	62.9	30.5	62.07	0.6427	61.4314	62.7169
72	61.8	30.5	62.07	0.6427	61.4314	62.7169
73	63.5	30.5	62.07	0.6427	61.4314	62.7169
74	62.6	30.5	62.07	0.6427	61.4314	62.7169
75	61.8	30.5	62.07	0.6427	61.4314	62.7169

No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
76	61.4	30.5	62.07	0.6427	61.4314	62.7169
77	60.6	30.5	62.07	0.6427	61.4314	62.7169
78	61.6	31.1	62.17	0.6662	61.5064	62.8389
79	59.8	31.7	62.27	0.6936	61.5795	62.9667
80	60.0	32.9	62.48	0.7602	61.7200	63.2405
81	64.9	32.9	62.48	0.7602	61.7200	63.2405
82	64.0	32.9	62.48	0.7602	61.7200	63.2405
83	62.1	32.9	62.48	0.7602	61.7200	63.2405
84	63.5	32.9	62.48	0.7602	61.7200	63.2405
85	63.2	32.9	62.48	0.7602	61.7200	63.2405
86	60.3	32.9	62.48	0.7602	61.7200	63.2405
87	60.2	33.5	62.59	0.7995	61.7877	63.3866
88	63.9	34.2	62.70	0.8427	61.8536	63.5390
89	59.9	35.6	62.92	0.9411	61.9809	63.8630
90	75.3	35.6	62.92	0.9411	61.9809	63.8630
91	62.8	35.6	62.92	0.9411	61.9809	63.8630
92	61.8	35.6	62.92	0.9411	61.9809	63.8630
93	66.0	35.6	62.92	0.9411	61.9809	63.8630
94	61.8	35.6	62.92	0.9411	61.9809	63.8630
95	61.0	35.6	62.92	0.9411	61.9809	63.8630
96	65.9	36.0	62.98	0.9682	62.0118	63.9481
97	66.8	37.2	63.16	1.0556	62.1024	64.2137
98	60.8	37.2	63.16	1.0556	62.1024	64.2137
99	65.9	38.9	63.41	1.1871	62.2185	64.5927
100	63.5	38.9	63.41	1.1871	62.2185	64.5927
101	64.2	38.9	63.41	1.1871	62.2185	64.5927
102	67.6	38.9	63.41	1.1871	62.2185	64.5927
103	59.1	38.9	63.41	1.1871	62.2185	64.5927
104	63.9	38.9	63.41	1.1871	62.2185	64.5927
105	65.3	38.9	63.41	1.1871	62.2185	64.5927
106	60.0	38.9	63.41	1.1871	62.2185	64.5927

M-2 CONFIDENCE INTERVALS FOR THE CURVE ESTIMATES OF NOISE–SPEED RELATIONSHIPS ACROSS 100 MM SPEED HUMP



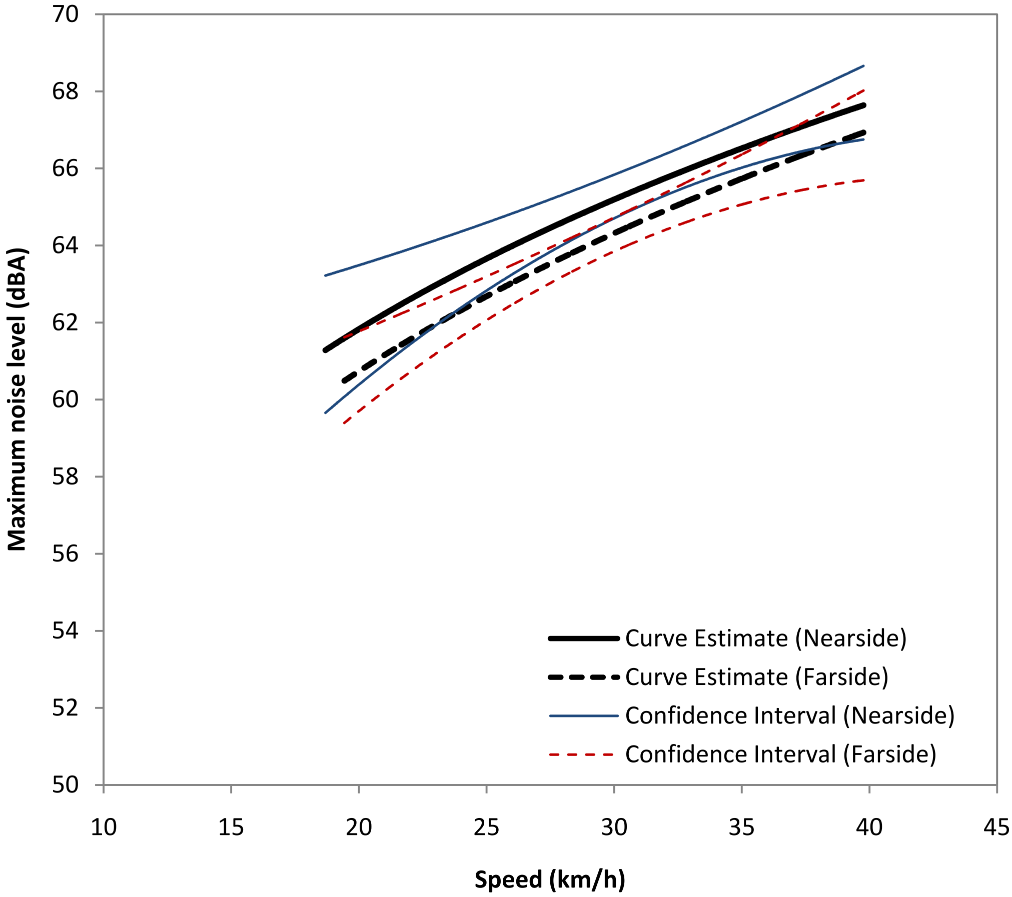
No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
1	61.1	13.8	61.50	0.9762	60.5270	62.4794
2	63.1	14.7	61.82	0.9098	60.9142	62.7337
3	65.8	15.8	62.17	0.8348	61.3347	63.0044
4	65.7	16.4	62.35	0.7938	61.5590	63.1466
5	61.2	16.4	62.35	0.7938	61.5590	63.1466
6	62.3	16.4	62.35	0.7938	61.5590	63.1466
7	60.4	16.4	62.35	0.7938	61.5590	63.1466
8	60.5	16.4	62.35	0.7938	61.5590	63.1466
9	63.1	17.1	62.54	0.7502	61.7936	63.2941
10	60.8	17.1	62.54	0.7502	61.7936	63.2941
11	61.3	17.1	62.54	0.7502	61.7936	63.2941
12	64.1	17.1	62.54	0.7502	61.7936	63.2941
13	60.6	17.8	62.74	0.7041	62.0392	63.4474
14	61.4	18.6	62.95	0.6555	62.2965	63.6074
15	60.1	18.6	62.95	0.6555	62.2965	63.6074
16	62.0	18.6	62.95	0.6555	62.2965	63.6074
17	60.2	18.6	62.95	0.6555	62.2965	63.6074
18	62.6	18.6	62.95	0.6555	62.2965	63.6074
19	66.1	18.6	62.95	0.6555	62.2965	63.6074
20	60.2	18.6	62.95	0.6555	62.2965	63.6074
21	62.8	19.4	63.17	0.6046	62.5660	63.7752

No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
22	60.6	19.4	63.17	0.6046	62.5660	63.7752
23	65.2	19.4	63.17	0.6046	62.5660	63.7752
24	62.8	19.4	63.17	0.6046	62.5660	63.7752
25	63.6	19.4	63.17	0.6046	62.5660	63.7752
26	64.8	19.4	63.17	0.6046	62.5660	63.7752
27	61.2	19.4	63.17	0.6046	62.5660	63.7752
28	64.0	19.4	63.17	0.6046	62.5660	63.7752
29	67.0	19.4	63.17	0.6046	62.5660	63.7752
30	63.2	20.1	63.34	0.5655	62.7763	63.9072
31	63.9	20.4	63.40	0.5523	62.8479	63.9526
32	63.4	20.4	63.40	0.5523	62.8479	63.9526
33	63.4	20.4	63.40	0.5523	62.8479	63.9526
34	64.6	20.4	63.40	0.5523	62.8479	63.9526
35	66.1	20.4	63.40	0.5523	62.8479	63.9526
36	60.8	20.4	63.40	0.5523	62.8479	63.9526
37	62.0	20.4	63.40	0.5523	62.8479	63.9526
38	60.1	20.4	63.40	0.5523	62.8479	63.9526
39	60.8	21.2	63.61	0.5066	63.1045	64.1176
40	65.4	21.4	63.64	0.5002	63.1418	64.1421
41	61.2	21.4	63.64	0.5002	63.1418	64.1421
42	65.3	21.4	63.64	0.5002	63.1418	64.1421
43	64.9	21.4	63.64	0.5002	63.1418	64.1421
44	64.0	21.4	63.64	0.5002	63.1418	64.1421
45	61.3	21.4	63.64	0.5002	63.1418	64.1421
46	61.6	21.4	63.64	0.5002	63.1418	64.1421
47	63.7	21.4	63.64	0.5002	63.1418	64.1421
48	62.1	21.4	63.66	0.4970	63.1606	64.1545
49	63.8	22.5	63.90	0.4513	63.4458	64.3484
50	63.0	22.5	63.90	0.4513	63.4458	64.3484
51	60.8	22.5	63.90	0.4513	63.4458	64.3484
52	64.6	22.5	63.90	0.4513	63.4458	64.3484
53	64.6	22.5	63.90	0.4513	63.4458	64.3484
54	62.5	22.5	63.90	0.4513	63.4458	64.3484
55	72.7	22.5	63.90	0.4513	63.4458	64.3484
56	66.4	22.5	63.90	0.4513	63.4458	64.3484
57	63.0	22.5	63.90	0.4513	63.4458	64.3484
58	62.2	22.5	63.90	0.4513	63.4458	64.3484
59	61.7	22.5	63.90	0.4513	63.4458	64.3484
60	67.3	22.5	63.90	0.4513	63.4458	64.3484
61	62.4	22.5	63.90	0.4513	63.4458	64.3484
62	68.9	23.4	64.10	0.4203	63.6778	64.5185
63	72.1	23.6	64.13	0.4159	63.7166	64.5485
64	62.4	23.7	64.15	0.4138	63.7360	64.5637
65	66.8	23.8	64.17	0.4118	63.7554	64.5790
66	62.4	23.8	64.17	0.4118	63.7554	64.5790
67	63.7	23.8	64.17	0.4118	63.7554	64.5790
68	66.3	23.8	64.17	0.4118	63.7554	64.5790
69	65.6	23.8	64.17	0.4118	63.7554	64.5790
70	66.3	23.8	64.17	0.4118	63.7554	64.5790
71	63.0	23.8	64.17	0.4118	63.7554	64.5790
72	71.3	23.8	64.17	0.4118	63.7554	64.5790
73	68.2	23.8	64.17	0.4118	63.7554	64.5790
74	65.3	23.8	64.17	0.4118	63.7554	64.5790
75	61.8	23.8	64.17	0.4118	63.7554	64.5790
76	62.6	23.8	64.17	0.4118	63.7554	64.5790
77	62.4	23.8	64.17	0.4118	63.7554	64.5790
78	63.5	23.8	64.17	0.4118	63.7554	64.5790
79	62.2	23.8	64.17	0.4118	63.7554	64.5790

No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
80	59.4	23.8	64.17	0.4118	63.7554	64.5790
81	63.8	23.8	64.17	0.4118	63.7554	64.5790
82	66.2	23.8	64.17	0.4118	63.7554	64.5790
83	63.3	24.0	64.22	0.4062	63.8134	64.6258
84	63.1	24.1	64.24	0.4045	63.8327	64.6417
85	68.4	24.4	64.31	0.3985	63.9098	64.7068
86	64.4	24.7	64.36	0.3950	63.9673	64.7574
87	64.4	25.1	64.45	0.3915	64.0624	64.8454
88	61.6	25.1	64.45	0.3915	64.0624	64.8454
89	58.1	25.1	64.45	0.3915	64.0624	64.8454
90	64.4	25.1	64.45	0.3915	64.0624	64.8454
91	65.6	25.1	64.45	0.3915	64.0624	64.8454
92	66.8	25.1	64.45	0.3915	64.0624	64.8454
93	67.2	25.1	64.45	0.3915	64.0624	64.8454
94	61.3	25.1	64.45	0.3915	64.0624	64.8454
95	70.4	25.1	64.45	0.3915	64.0624	64.8454
96	61.4	25.1	64.45	0.3915	64.0624	64.8454
97	62.4	25.1	64.45	0.3915	64.0624	64.8454
98	68.3	25.1	64.45	0.3915	64.0624	64.8454
99	65.7	25.1	64.45	0.3915	64.0624	64.8454
100	62.2	25.1	64.45	0.3915	64.0624	64.8454
101	67.0	25.1	64.45	0.3915	64.0624	64.8454
102	74.0	25.1	64.45	0.3915	64.0624	64.8454
103	59.1	25.1	64.45	0.3915	64.0624	64.8454
104	65.4	25.2	64.47	0.3912	64.0812	64.8636
105	63.9	25.3	64.49	0.3909	64.1001	64.8819
106	65.9	25.3	64.49	0.3909	64.1001	64.8819
107	66.4	25.5	64.53	0.3909	64.1375	64.9193
108	65.3	26.1	64.64	0.3942	64.2483	65.0367
109	62.2	26.7	64.76	0.4030	64.3564	65.1624
110	64.0	26.7	64.76	0.4030	64.3564	65.1624
111	66.1	26.7	64.76	0.4030	64.3564	65.1624
112	64.8	26.7	64.76	0.4030	64.3564	65.1624
113	67.0	26.7	64.76	0.4030	64.3564	65.1624
114	66.0	26.7	64.76	0.4030	64.3564	65.1624
115	65.3	26.7	64.76	0.4030	64.3564	65.1624
116	65.0	26.7	64.76	0.4030	64.3564	65.1624
117	62.4	26.7	64.76	0.4030	64.3564	65.1624
118	66.3	26.7	64.76	0.4030	64.3564	65.1624
119	65.1	26.7	64.76	0.4030	64.3564	65.1624
120	64.5	26.7	64.76	0.4030	64.3564	65.1624
121	65.2	26.7	64.76	0.4030	64.3564	65.1624
122	63.6	26.8	64.78	0.4051	64.3741	65.1842
123	61.7	26.8	64.78	0.4051	64.3741	65.1842
124	66.0	26.8	64.78	0.4051	64.3741	65.1842
125	61.3	28.0	65.00	0.4387	64.5636	65.4411
126	67.2	28.1	65.02	0.4428	64.5804	65.4660
127	65.2	28.5	65.09	0.4561	64.6301	65.5423
128	64.8	28.5	65.09	0.4561	64.6301	65.5423
129	67.6	28.5	65.09	0.4561	64.6301	65.5423
130	63.2	28.5	65.09	0.4561	64.6301	65.5423
131	64.1	28.5	65.09	0.4561	64.6301	65.5423
132	65.5	28.5	65.09	0.4561	64.6301	65.5423
133	65.0	28.5	65.09	0.4561	64.6301	65.5423
134	64.1	28.5	65.09	0.4561	64.6301	65.5423
135	66.8	28.5	65.09	0.4561	64.6301	65.5423
136	71.6	28.5	65.09	0.4561	64.6301	65.5423
137	70.0	28.5	65.09	0.4561	64.6301	65.5423

No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
138	69.3	28.5	65.09	0.4561	64.6301	65.5423
139	66.5	28.5	65.09	0.4561	64.6301	65.5423
140	60.8	28.5	65.09	0.4561	64.6301	65.5423
141	62.5	29.0	65.17	0.4763	64.6953	65.6479
142	63.3	29.0	65.17	0.4763	64.6953	65.6479
143	62.5	29.5	65.26	0.4992	64.7593	65.7578
144	62.5	30.1	65.37	0.5317	64.8378	65.9012
145	60.0	30.5	65.44	0.5532	64.8842	65.9906
146	67.4	30.5	65.44	0.5532	64.8842	65.9906
147	66.3	30.5	65.44	0.5532	64.8842	65.9906
148	63.2	30.5	65.44	0.5532	64.8842	65.9906
149	63.1	30.5	65.44	0.5532	64.8842	65.9906
150	63.2	30.5	65.44	0.5532	64.8842	65.9906
151	64.5	30.5	65.44	0.5532	64.8842	65.9906
152	65.9	30.5	65.44	0.5532	64.8842	65.9906
153	66.4	30.5	65.44	0.5532	64.8842	65.9906
154	65.1	30.5	65.44	0.5532	64.8842	65.9906
155	62.7	30.5	65.44	0.5532	64.8842	65.9906
156	64.3	30.5	65.44	0.5532	64.8842	65.9906
157	65.7	30.5	65.44	0.5532	64.8842	65.9906
158	68.5	30.5	65.44	0.5532	64.8842	65.9906
159	63.6	30.5	65.44	0.5532	64.8842	65.9906
160	63.5	30.5	65.44	0.5532	64.8842	65.9906
161	61.6	30.5	65.44	0.5532	64.8842	65.9906
162	75.9	30.5	65.44	0.5532	64.8842	65.9906
163	68.0	30.5	65.44	0.5532	64.8842	65.9906
164	65.5	30.5	65.44	0.5532	64.8842	65.9906
165	67.4	30.8	65.48	0.5683	64.9149	66.0515
166	61.4	31.7	65.62	0.6177	65.0056	66.2410
167	66.6	32.9	65.82	0.6927	65.1241	66.5094
168	61.6	32.9	65.82	0.6927	65.1241	66.5094
169	66.6	32.9	65.82	0.6927	65.1241	66.5094
170	62.0	32.9	65.82	0.6927	65.1241	66.5094
171	69.0	32.9	65.82	0.6927	65.1241	66.5094
172	68.4	32.9	65.82	0.6927	65.1241	66.5094
173	66.0	32.9	65.82	0.6927	65.1241	66.5094
174	66.6	32.9	65.82	0.6927	65.1241	66.5094
175	65.1	32.9	65.82	0.6927	65.1241	66.5094
176	66.2	32.9	65.82	0.6927	65.1241	66.5094
177	67.0	32.9	65.82	0.6927	65.1241	66.5094
178	69.6	32.9	65.82	0.6927	65.1241	66.5094
179	61.8	33.4	65.89	0.7235	65.1679	66.6149
180	66.6	35.1	66.15	0.8371	65.3118	66.9860
181	63.7	35.6	66.23	0.8745	65.3544	67.1035
182	68.0	35.6	66.23	0.8745	65.3544	67.1035
183	66.1	35.6	66.23	0.8745	65.3544	67.1035
184	67.3	35.6	66.23	0.8745	65.3544	67.1035
185	65.3	35.6	66.23	0.8745	65.3544	67.1035
186	62.5	35.6	66.23	0.8745	65.3544	67.1035
187	68.3	35.6	66.23	0.8745	65.3544	67.1035
188	68.8	38.9	66.68	1.1026	65.5774	67.7826

M-3 CONFIDENCE INTERVALS FOR THE CURVE ESTIMATES OF NOISE–SPEED RELATIONSHIPS ACROSS FLAT SECTION OF ROAD



No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
1	65.0	18.7	61.35	1.5724	59.7762	62.9210
2	62.1	21.4	62.44	1.2966	61.1410	63.7341
3	66.1	22.5	62.86	1.1838	61.6747	64.0423
4	67.0	23.8	63.31	1.0613	62.2441	64.3666
5	57.3	23.8	63.31	1.0613	62.2441	64.3666
6	60.9	24.0	63.39	1.0372	62.3550	64.4294
7	62.1	25.1	63.78	0.9292	62.8520	64.7103
8	64.8	25.1	63.78	0.9292	62.8520	64.7103
9	63.0	26.7	64.29	0.7897	63.4999	65.0794
10	60.2	26.7	64.29	0.7897	63.4999	65.0794
11	62.5	26.7	64.29	0.7897	63.4999	65.0794
12	64.7	26.9	64.34	0.7765	63.5627	65.1157
13	64.7	27.4	64.49	0.7369	63.7528	65.2266
14	65.4	27.4	64.49	0.7369	63.7528	65.2266
15	70.0	28.1	64.73	0.6763	64.0538	65.4064
16	69.6	28.5	64.84	0.6512	64.1843	65.4867
17	64.0	28.5	64.84	0.6512	64.1843	65.4867
18	69.7	28.5	64.84	0.6512	64.1843	65.4867
19	66.3	28.5	64.84	0.6512	64.1843	65.4867
20	63.3	28.5	64.84	0.6512	64.1843	65.4867
21	62.9	28.5	64.84	0.6512	64.1843	65.4867

No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
22	65.1	28.5	64.84	0.6512	64.1843	65.4867
23	63.1	28.5	64.84	0.6512	64.1843	65.4867
24	60.8	28.5	64.84	0.6512	64.1843	65.4867
25	64.3	29.2	65.05	0.6035	64.4474	65.6544
26	67.4	29.5	65.12	0.5887	64.5354	65.7128
27	63.9	30.0	65.27	0.5614	64.7113	65.8340
28	65.2	30.5	65.42	0.5379	64.8862	65.9621
29	63.8	30.5	65.42	0.5379	64.8862	65.9621
30	65.0	30.5	65.42	0.5379	64.8862	65.9621
31	63.5	30.5	65.42	0.5379	64.8862	65.9621
32	66.2	30.5	65.42	0.5379	64.8862	65.9621
33	63.2	30.5	65.42	0.5379	64.8862	65.9621
34	63.7	30.5	65.42	0.5379	64.8862	65.9621
35	67.6	30.5	65.42	0.5379	64.8862	65.9621
36	66.5	30.5	65.42	0.5379	64.8862	65.9621
37	66.4	30.5	65.42	0.5379	64.8862	65.9621
38	66.4	30.5	65.42	0.5379	64.8862	65.9621
39	67.8	30.5	65.42	0.5379	64.8862	65.9621
40	64.1	30.5	65.42	0.5379	64.8862	65.9621
41	63.9	30.5	65.42	0.5379	64.8862	65.9621
42	61.9	31.2	65.62	0.5159	65.1020	66.1338
43	64.1	31.7	65.74	0.5076	65.2290	66.2442
44	64.2	31.7	65.74	0.5076	65.2290	66.2442
45	66.0	32.6	65.98	0.5045	65.4752	66.4841
46	65.6	32.6	65.98	0.5045	65.4752	66.4841
47	65.7	32.9	66.06	0.5079	65.5545	66.5703
48	64.7	32.9	66.06	0.5079	65.5545	66.5703
49	62.7	32.9	66.06	0.5079	65.5545	66.5703
50	63.6	32.9	66.06	0.5079	65.5545	66.5703
51	64.5	32.9	66.06	0.5079	65.5545	66.5703
52	68.5	32.9	66.06	0.5079	65.5545	66.5703
53	66.3	32.9	66.06	0.5079	65.5545	66.5703
54	64.4	32.9	66.06	0.5079	65.5545	66.5703
55	65.1	32.9	66.06	0.5079	65.5545	66.5703
56	66.5	32.9	66.06	0.5079	65.5545	66.5703
57	71.4	32.9	66.06	0.5079	65.5545	66.5703
58	63.2	32.9	66.06	0.5079	65.5545	66.5703
59	65.6	32.9	66.06	0.5079	65.5545	66.5703
60	62.3	32.9	66.06	0.5079	65.5545	66.5703
61	66.4	33.4	66.19	0.5176	65.6706	66.7059
62	64.0	33.5	66.23	0.5221	65.7085	66.7528
63	66.7	33.9	66.32	0.5329	65.7832	66.8491
64	68.3	34.5	66.49	0.5621	65.9281	67.0523
65	65.4	35.6	66.76	0.6239	66.1348	67.3826
66	68.0	35.6	66.76	0.6239	66.1348	67.3826
67	70.2	35.6	66.76	0.6239	66.1348	67.3826
68	69.1	35.6	66.76	0.6239	66.1348	67.3826
69	68.2	35.6	66.76	0.6239	66.1348	67.3826
70	67.3	35.6	66.76	0.6239	66.1348	67.3826
71	64.5	35.6	66.76	0.6239	66.1348	67.3826
72	68.8	35.6	66.76	0.6239	66.1348	67.3826
73	74.4	35.6	66.76	0.6239	66.1348	67.3826
74	67.0	35.6	66.76	0.6239	66.1348	67.3826
75	69.7	35.6	66.76	0.6239	66.1348	67.3826
76	67.2	35.6	66.76	0.6239	66.1348	67.3826
77	65.9	35.6	66.76	0.6239	66.1348	67.3826
78	68.1	36.0	66.85	0.6491	66.2013	67.4994
79	66.3	36.2	66.90	0.6625	66.2342	67.5591

No.	L_{AFmax}	V	Estimated L_{AFmax}	CI	Lower CI	Upper CI
80	67.4	36.4	66.94	0.6764	66.2667	67.6195
81	59.9	38.9	67.52	0.8818	66.6423	68.4058
82	69.1	38.9	67.52	0.8818	66.6423	68.4058
83	70.8	38.9	67.52	0.8818	66.6423	68.4058
84	68.1	38.9	67.52	0.8818	66.6423	68.4058
85	66.1	38.9	67.52	0.8818	66.6423	68.4058
86	67.5	38.9	67.52	0.8818	66.6423	68.4058
87	68.7	38.9	67.52	0.8818	66.6423	68.4058
88	67.3	38.9	67.52	0.8818	66.6423	68.4058
89	65.1	38.9	67.52	0.8818	66.6423	68.4058
90	65.2	38.9	67.52	0.8818	66.6423	68.4058
91	69.5	38.9	67.52	0.8818	66.6423	68.4058
92	70.5	38.9	67.52	0.8818	66.6423	68.4058
93	71.1	38.9	67.52	0.8818	66.6423	68.4058
94	65.7	39.1	67.57	0.9019	66.6726	68.4763
95	66.2	39.3	67.63	0.9224	66.7028	68.5476
96	65.9	39.8	67.73	0.9649	66.7629	68.6926

Appendix N

N-1 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MAXIMUM NOISE LEVELS ON NEARSIDE AND FARSIDE LANES ACROSS 75 MM SPEED HUMP

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance on the nearside lane is smaller

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	p-value
0.6643	1.3819	0.9812

Since F <= Critical F, reject the null hypothesis.
The variance on the nearside lane is smaller.

t-Test: Two-Sample (Unequal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	Nearside	*Farside*
Mean	61.41481	59.36467
Variance	10.72553	16.14573
Observations	106	105
df	200	
t Stat	4.060264	
P(T<=t) two-tail	7.03E-05	
t Critical two-tail	1.971896	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.

N-2 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MAXIMUM NOISE LEVELS ON NEARSIDE AND FARSIDE LANES ACROSS 100 MM SPEED HUMP

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance on the nearside lane is larger

F-test Statistic, F	Critical $_{F(\alpha,n-1,m-1)}$	p-value
1.1036	1.2574	0.2390

Since F <= Critical F, accept the null hypothesis.
The variances are equal.

t-Test: Two-Sample (Equal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	Nearside	*Farside*
Mean	64.48351	62.89692
Variance	8.378818	7.592424
Observations	188	227
Pooled Variance	7.948491	
df	413	
t Stat	5.706783	
P(T<=t) two-tail	2.2E-08	
t Critical two-tail	1.965724	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.

N-3 F-TEST FOR EQUALITY OF VARIANCES AND T-TEST FOR COMPARISON OF MAXIMUM NOISE LEVELS ON NEARSIDE AND FARSIDE LANES ACROSS FLAT SECTION OF ROAD

F-Test

Null hypothesis : The variances are equal
Alternative hypothesis : The variance on the nearside lane is larger

F-test Statistic, F	Critical $F_{(\alpha,n-1,m-1)}$	p-value
1.0374	1.3672	0.4207

Since F <= Critical F, accept the null hypothesis.
The variances are equal.

t-Test: Two-Sample (Equal Variances)

Null hypothesis: The means are the same
Alternative hypothesis: The means are significantly different

	Nearside	*Farside*
Mean	65.7824	64.08398
Variance	7.823383	7.541653
Observations	96	128
Pooled Variance	7.662213	
df	222	
t Stat	4.544461	
P(T<=t) two-tail	9.05E-06	
t Critical two-tail	1.970707	

Since p <= 0.05, reject the null hypothesis.
The means are significantly different.